SECTION 20—WEAPONS EFFECTS TECHNOLOGY

Scope

Highlights

- This section includes nuclear and nonnuclear weapons effects since nuclear effects must be considered in future conflicts.
- Because nuclear effects are included, the critical technical parameters, materials, and technical issues are usually determined by the nuclear requirements.
- Weapons effects technologies include predictions using validated computer codes and experiments and physical simulators that mimic the environments produced by the various effects. Weapons effects technology is used to evaluate the vulnerabilities of potential targets and delivery systems.
- Each type of weapon effect (shock waves, hard target penetration, thermal radiation, ionizing radiation, and electromagnetic effects) requires its own set of physical simulators and predictions from validated computer codes. Few simulators are able to replicate more than one weapon effect.
- Physical simulators and validated codes require large financial investments.

OVERVIEW

This section addresses six technologies that are used to evaluate the survivability and hardening (S&H) of military systems against the effects of nuclear and nonnuclear weapons. These six areas[1] were selected to include nuclear and nonnuclear considerations efficiently. The end of the Cold War has caused an overall dramatic reduction in the development of new technologies that are unique to nuclear weapons. In recent years, the emphasis on nuclear weapon effects on systems has diminished in comparison with the emphasis on the effects of high-energy lasers (HELs), charged particle beams (CPBs), neutral particle beams (NPBs), high-power microwaves (HPMs), and hard target penetrating weapons (PWs).

In contrast to nuclear-unique weapons effects, where emerging technologies receive only limited support, strong research activities continue in those areas where the overlap between nuclear and nonnuclear technology is significant. A prime example is the electromagnetic effects on systems. Hard target penetration is an area that overlaps modestly with nuclear weapons effects and in which the level of research and development (R&D) is solid.

[1] Shock waves, hard target penetration, thermal radiation, ionizing radiation, electromagnetic effects, and underground weapons effects simulation.

SECTION 20.1—SHOCK WAVES

Highlights

- Blast and shock effects produced by low-altitude nuclear weapons that have yields below about 1 Mt are the primary damage-producing mechanisms for cities and other nonmilitary hardened structures. Considerable overlap exists between the dynamic pressure regime of nuclear-produced blast waves and those of air drag produced by strong hurricanes.
- Nuclear airblasts have a longer time duration and a larger overpressure than conventional chemical explosions. Their effects on systems can be simulated with chemical explosions using scaling theory.
- Ground shock produced by nuclear detonations is often the only effective mechanism for destroying underground bunkers and deeply buried missile silos.
- The three types of ground shock are airblast-induced ground shock, direct-induced ground shock, and crater-related ground motion.
- Underwater shock is similar to an airblast in theoretical respects. Experiments using scaling theory are often effective in simulating the effects of underwater shock on surface and submerged vessels.
- Endoatmospheric nuclear detonations can adversely affect low-altitude airborne systems by airblast, thermal radiation, and lofted dust and debris.
- X-rays produced by exoatmospheric nuclear detonations can adversely affect space platforms via thermo-mechanical shock (TMS).

OVERVIEW

This section addresses blast and shock effects to military systems produced by nuclear and nonnuclear detonations. It covers airblast, ground shock, underwater shock, and aerospace structure shock. Determining the blast and shock effects on military systems requires determining the environment and the hardness of the structures against the blast and shock waves. Simulating the effects of these blast and shock on structures is critical for assessing the structures' survivability.

Although nuclear-augmented blast and shock waves are capable of producing overpressures and stresses well beyond those that can be achieved with conventional explosives, the technology for hardening structures against nuclear blast and shocks effects is essentially the same as that for the nonnuclear case. Application of established principles appears to suffice in both cases. For this reason, our discussions emphasize the nuclear effects, since this is the most stressing case from a technology viewpoint.

Airblast is discussed first since this is perhaps the phenomenon with which we are most familiar. This is followed by a discussion of ground shock. The effects of an underwater detonation, whether conducted in a deep or a shallow situation, have features that are similar to airblast and ground shock, and these effects are discussed next. The last topic is the survivability of aerospace structures. In space, the effects are caused exclusively by the nuclear case(s): dust generated on aerospace systems by low-altitude nuclear detonations and X-ray-induced TMS generated on space platforms by high-altitude nuclear detonations.

BACKGROUND

Airblast

As pictures of Hiroshima, Nagasaki, and the test structures erected at the Nevada Test Site in the 1950s amply demonstrate, the blast and shock waves produced by nuclear explosions are the principal means for destroying soft targets. In the absence of atmospheric and underground nuclear testing to determine the survivability of structures, we must find the means to simulate the phenomena associated with a nuclear explosion. For airblast, this can be done either in a large-scale, open-air test employing chemical explosives or in a specially designed test facility that can also produce thermal fluxes comparable to those from a nuclear weapon.

More recently, U.S. attention has focused on pressure regimes that are higher than those that can be attained in open-air testing and on testing techniques that use large simulators capable of reproducing simultaneously the blast and the thermal pulse from a nuclear detonation. These simulators typically employ a fuel-oxygen mixture (e.g., liquid oxygen and finely powdered aluminum) and consist of long semicircular tubes. These simulators can even approximate the effects of soil type on blast-wave propagation and the entraining of dust in the blast wave.

The actual combination of the overpressure, dynamic pressure, lift, and diffraction effects on a target is exceedingly difficult to model analytically or to simulate numerically, particularly without actual data. In the pressure regime characteristic of nuclear weapons, military interest in the effects of dynamic loading on systems centers on the survivability of tracked and wheeled vehicles, towed vehicles, command, control, and communications (C3) shelters, and so forth. Civilian interest is in the survivability of similar systems and structures subjected to storm winds. The two are not completely distinct interests because the dynamic pressure from strong hurricanes can be comparable to that from nuclear blasts.

Military interest also focuses on shock loading, a dynamic process that differs from the nearly steady-state effects of storm winds. As a rule of thumb, a 30-kPa pressure threshold corresponding to a 60 m/sec particle velocity in the shock or a drag force equivalent to that produced by about 210 km/hr (130 mph) steady winds distinguishes the military and civilian applications. A frequently used design objective for civil structures is survivability in 190 km/hr (120 mph) winds.

Ground Shock

Predicting the ground shock/motion (including cratering) produced by a nuclear weapon detonation is essential for determining the survivability and hardness of surface-flush structures, shallow-buried structures (foundation < 30 m deep/cut-and-cover construction), and deeply buried structures (constructed using tunneling methods). Ground shock from a low-altitude, surface, or underground burst may be the only way to destroy hardened underground structures such as command facilities or missile silos.

Surface-flush structures are typically missile silos, while shallow-buried structures are typically used for C3, personnel protection, and missile launch control. The environments of primary interest for each are consistent with peak overpressures from approximately 1 MPa to an upper limit of perhaps 1 GPa. For deeply buried structures, interests are from about 25 MPa to the nuclear weapon source. Structural response interest ranges from peak stresses of 25 to 500 MPa.

Ground shock has three dominant components: airblast-induced ground shock, direct-induced ground shock, and crater-related ground motion. Airblast-induced ground shock is caused by the airblast interaction with the ground. Direct-induced ground shock and crater-related ground motion are caused by the direct interaction of weapon debris and thermal radiation with the ground and are viewed as components of the source-induced ground shock. Figure 20.1-1 shows the ground shock created by all three components for a burst that occurs just above the earth's surface. Surface waves also develop at the free-surface boundary between the air and ground; however, this discussion does not include these waves, which are relatively low in amplitude and not generally important.

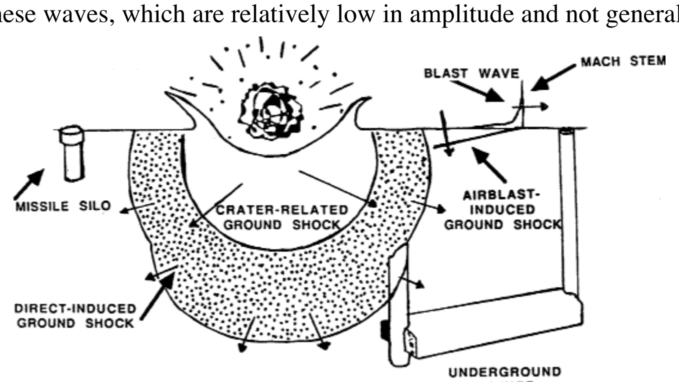


Figure 20.1-1. Three Components of Ground Shock (Source: Reference 1)

Many of the essential physical features of the extremely high pressures and temperatures of nuclear-generated ground shock have some commonality with nonnuclear considerations. This latter category includes hypervelocity impact effects produced by kinetic energy weapons (KEWs), such as the development of craters and mass ejection from the target. Moreover, many of the truly advanced computational techniques for calculating the transient behavior of materials at high temperatures and pressures apply in both cases.

Underwater Shock

An underwater nuclear explosion releases large amounts of thermal energy and nuclear radiation that are absorbed within a few feet of the explosion. This intense energy deposition creates a hot gas bubble, which is formed by the vaporization of the water and expands rapidly. A shock wave similar to that created by a nuclear explosion in air is formed. Because the shock-wave generation is similar in both cases, scaling relationships, which play a large role in understanding and simulating an airburst, are also relevant for simulating underwater explosions.

Before the introduction of nuclear weapons into the military arsenal, interest in underwater explosions focused on bombs, depth charges, and torpedo warheads. Some excellent scientific papers and reports address the theory and simulation of nonnuclear underwater explosions.

Besides the physical damage to the vessels and aircraft, the radioactive fallout generated by the water spray threatens life. Winds can carry this fallout great distances from the burst. Blueout is another effect of military interest. This condition arises when the intensity of the primary shock wave falls to levels where it becomes an ordinary acoustic wave disturbance. The wave bounces back and forth between reflecting surfaces (e.g., the ocean floor and water surface) and is said to reverberate. When this occurs, the coherence of the initial wave front is lost, and the energy of the wave becomes part of the background noise.

Figure 20.1-2 is an overview of the effects produced by an underwater explosion. As observed, several different effects can adversely affect military systems.

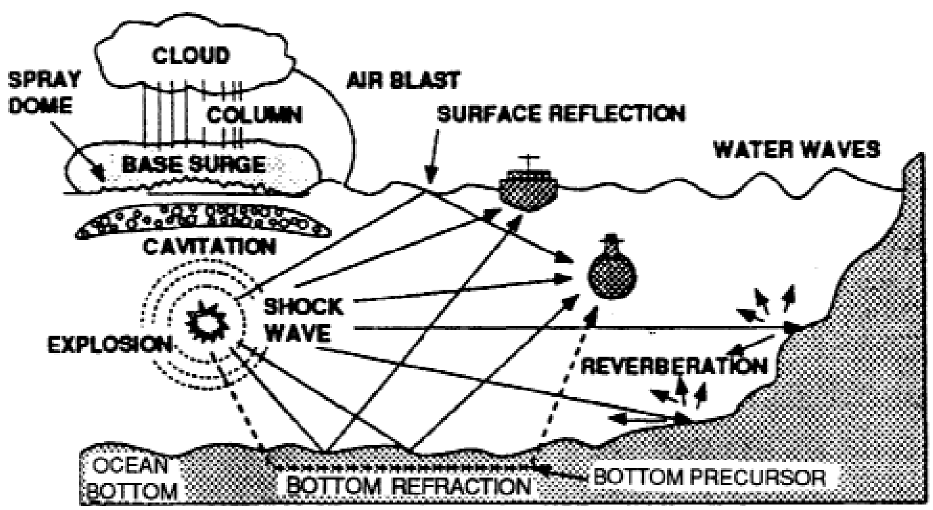


Figure 20.1-2. Overview of Effects Produced by an Underwater Nuclear Detonation (Source: Reference 2)

Aerospace Structure Shock

The technologies in this area are concerned with improving the survivability of aircraft and helicopters (including crew), reentry bodies, and space platforms against a variety of different effects caused by nuclear-generated shock waves. The nonnuclear domain appears to have no counterparts to this set of technologies.

Two categories of nuclear-produced shock waves are of interest. The first category is concerned with the three effects caused by a low-altitude nuclear detonation (an endoatmospheric burst): airblast, thermal radiation, and dust/pebbles generated at the ground and lofted to higher altitudes. Airblast can affect the motion of an airborne platform and can cause structural damage. Thermal radiation can weaken the structure and damage optical sensors and detectors. Airblast below about 50 kPa, in conjunction with the thermal environment (especially for tactical yield nuclear explosions), is of primary importance. Dust and pebbles are important during intercontinental ballistic missile (ICBM) fly-out. Dust can be important to reentry vehicle (RV) survival in the target area and also to aircraft engine performance and windshields.

The second category is concerned with the effects caused by a high-altitude nuclear detonation (an exoatmospheric burst). These effects are vastly different from those of a low-altitude nuclear detonation. A high-altitude nuclear detonation produces a copious source of X-rays. These X-rays travel from the location of the detonation to the space platform and strike its surface, where they are absorbed in a thin layer. The impulse created by this effect generates a shock wave that travels through the space platform. This is called TMS, or thermomechanical shock, and it can produce physical damage to the platform.

Issues regarding the survivability of military systems against endoatmospheric nuclear detonations include the avoidance of nuclear-generated dust clouds, transport of dust clouds, and characterization of dust clouds; fratricide and engine damage effects on aircraft; and the determination of dust lofting by the airblast.

Figure 20.1-3 shows the generation of a nuclear dust cloud. This cloud consists of the dust lofted in the characteristic mushroom formation, caused by the direct interaction of the airblast with the ground and of the dust swept up off the ground surface by the airblast. Both components of dust are transported downwind by the ambient atmospheric winds.

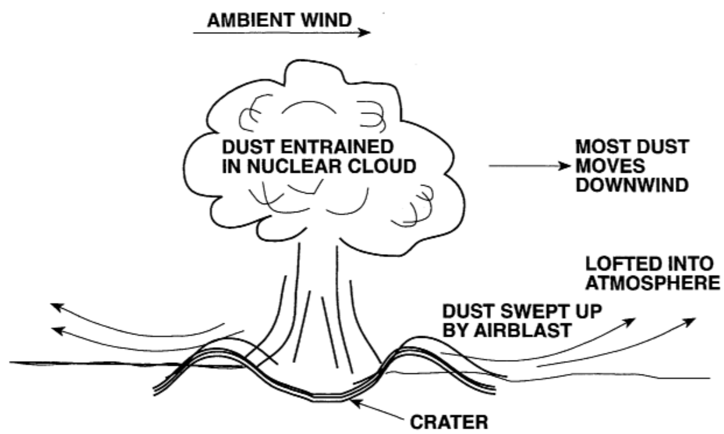


Figure 20.1-3. Generation of Nuclear Dust Cloud

CITED REFERENCES

1. “Ground Shock From Nuclear Weapons,” Brochure published by Defense Nuclear Agency, September 1991.
2. “Underwater Nuclear Explosions,” Brochure published by Defense Nuclear Agency, December 1992.

LIST OF TECHNOLOGY DATA SHEETS
20.1. SHOCK WAVES

DATA SHEET 20.1. AIRBLAST PREDICTION

Developing Critical Technology Parameter	Theoretical models and related computer programs that compute the blast-wave environment from a nuclear detonation or a physical simulation of a nuclear detonation. The pressure range of interest is ≥ 30 kPa. The models should be capable of accommodating nuclear yields from the kiloton to the megaton range and in altitudes up to 40 km.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes and related mathematical algorithms that have been compared with nuclear detonations or simulations of a nuclear detonation including input parameters, such as equation of state (EOS) and material properties. Of particular interest are those that have been specially designed to predict the airblast over real ground (not ideal surfaces), including such features as dust, snow, rain, hills, valleys, vegetation, and so forth. These models should also be capable of heating the ground by thermal radiation generated by low-altitude nuclear detonations, an effect that leads to the generation of a precursor shock wave.
Major Commercial Applications	Explosions in the air.
Affordability	In most cases, open literature models and computer codes are available.

BACKGROUND

The earliest practical theory of the generation of blast waves in air is attributed to the early work of G.I. Taylor. Although his work was initiated for conventional explosives, the theory readily applies to nuclear detonations. L.I. Sedov made a major improvement to Taylor's theory by introducing the application of dimensional analysis. In the United States, M.L. Brode has made significant contributions to nuclear blast-wave theory, particularly in the area of interpreting experimental data to theoretical models.

We have a very good understanding of free airblast wave theory and blast waves over an ideal ground. The theory of an airblast over a nonideal ground requires further research. Several factors can make a ground surface nonideal (e.g., surfaces that are hilly, surfaces that can absorb the heat generated by the fireball, and surfaces that are capable of generating dust). Blast-wave effects are more pronounced on the slopes facing the detonation because of reflection and are diminished on the opposite sides because of rarefactions.

Thermal radiation absorbed into the earth's surface can raise the temperature in the top layer of the earth and the temperature of the air just above it. This heated air is called a "thermal layer" and typically contains dust, smoke, and particulate matter. The shock velocity is higher in the thermal layer and, as a result, forms a "precursor" shock front that travels faster than the main blast wave associated with the Mach Stem.

The dust lofting and increased dynamic pressure associated with the precursor enhance the potential damaging effects of this type of shock wave. Predicting precursor characteristics is difficult because of the complex interactions of the ground and lofted dust. Meaningful predictions require sophisticated computer models.

Since shock waves traveling in a porous medium have lower velocities than those traveling in a nonporous medium, airblasts over porous mediums lead to the generation of a "decursor" shock wave. This case is opposite that of the precursor case since the shock front in the air arrives before the one propagating along the earth's surface. Although the theoretical formulation of the decursor problem is formidable, publications in this area based on first principles should not be controlled.

DATA SHEET 20.1. AIRBLAST SIMULATOR

Developing Critical Technology Parameter	Overpressure and/or dynamic pressure levels exceeding 3 kPa, dust generated by nuclear burst with scaled HOB below 250m/(KT)$^{1/3}$, and all high-yield bursts at higher HOB for high-humidity layers below 3,000 m above sea level.
Critical Materials	Dilute explosives mixed with inert materials (such as dilute explosive tiles) can produce a more uniform detonation that more closely resembles a nuclear detonation. Using these dilute explosives gets rid of unwanted local intense high-pressure regions formed by the interaction of discrete shock waves generated by lumped explosives. These dilute explosives also enable the testing of structures down to 15,000 psi, which covers a wide variety of military objects.
Unique Test, Production, Inspection Equipment	Miniaturized gauges that can measure pressure and structural response; shock tubes or other devices that can simulate the nonideal nuclear airblast environment.
Unique Software	Substantiated computer codes and algorithms that predict the pressure waveform generated by a nuclear airblast and that can be used for designing the simulator and for calibration.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Because the calculation of shock effects generated by a nuclear weapon is extremely difficult to model, we must develop a more accurate quantitative basis using simulation techniques. The use of high explosives to simulate nuclear effects is based, in part, on scaling theory and the fact that certain explosives can simulate the peak overpressure and temporal variation of pressure over useful ranges.

DATA SHEET 20.1. THERMAL/BLAST SIMULATOR

Developing Critical Technology Parameter	3,000-K-equivalent blackbody radiation sources, pulse-length 0–10 sec, surface emittance > 8 cal/cm^2-sec, that can test subsystems and systems against combined thermal and blast effects of a low-altitude nuclear detonation.
Critical Materials	Liquid oxygen; powdered aluminum (micron range).
Unique Test, Production, Inspection Equipment	Instrumentation for measuring the response of systems and materials for flux levels > 8 cal/cm^2-sec; cameras with spectral resolution < 0.25 nm, sampling rate > 120/sec, and 10-bit resolution.
Unique Software	Substantiated computer codes and algorithms that can interpret and extrapolate the results from simulation to real systems and include the response of materials at elevated temperature and temperature gradients in the presence of shock waves.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

Despite the significant technical achievements of the high-explosive program, these simulators do not have the size or capability for full-scale, high-yield survivability testing. To meet this requirement, the Large Blast/Thermo Simulator (LB/TS) was developed. Figure 20.1-4 is an illustration of the LB/TS.

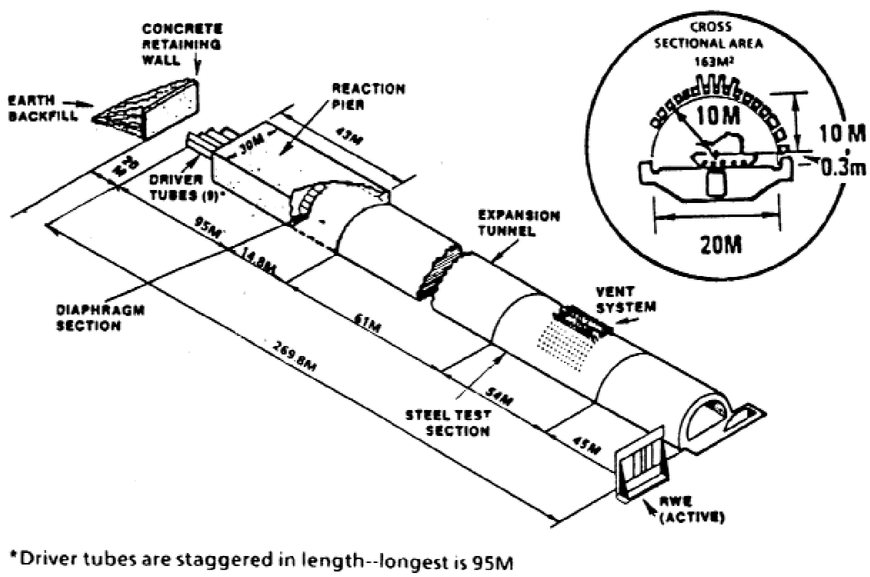


Figure 20.1-4. Illustration of the LB/TS (Source: Reference 1)

Note for Figure 20.1-4: *All dimensions are approximate.*

The LB/TS is capable of simulating nuclear blast and thermal effects on full-scale tactical systems, mostly for Army applications. The LB/TS can generate simulated yields of 600 kt, which are required for survivability testing. When contrasted with the upper limit of 16 kt for high-explosive simulation techniques, this capability is a tremendous improvement. Figure 20.1-5 compares the blast capabilities of the LB/TS with the Army's tactical

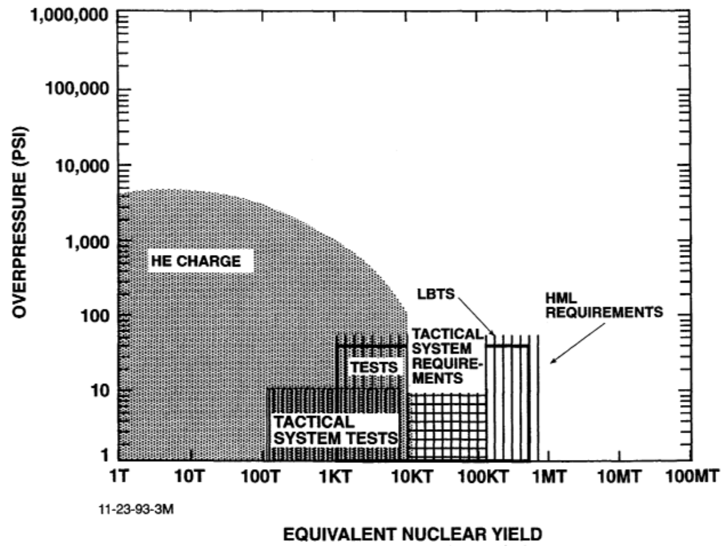


Figure 20.1-5. Blast Capabilities vs. Requirements for the LB/TS (Source: Reference 1)

system requirements and with the Hardened Missile Launch (HML) requirements. Also shown for comparison are the capabilities of high-explosive simulation. The LB/TS is the state-of-the-art technology for nuclear thermal and blast simulation.

CITED REFERENCE

1. "Large Blast/Thermal Simulator (LB/TS)," Brochure published by the Defense Nuclear Agency, July 1989.

DATA SHEET 20.1. RIGID BODY DISPLACEMENT

Developing Critical Technology Parameter	Techniques for eliminating or reducing the rigid-body displacement, translation, and overturn of land-mobile vehicles when subjected to airblasts ≥ 30 kPa without adverse effect on vehicle weight, mobility, dash responsiveness, or signature.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Mathematical models and computer algorithms that can predict the torques on mobile vehicles caused by blast waves and ways to mitigate against these unbalancing forces. Of particular interest are those models and algorithms that have been validated against airblast simulations.
Major Commercial Applications	Commercial vehicles in presence of strong wind.
Affordability	Inexpensive.

BACKGROUND

The military interest is in methods to increase the survivability of land-mobile systems that are subjected nuclear airblast. These systems include tracked and wheeled vehicles, towed vehicles, C3 shelters, mobile radar, mobile missiles, and so forth. The civilian interest is in the survivability of mobile and movable systems under storm wind conditions. These include trucks, automobiles, and mobile homes that are quasi-permanently sited in trailer camps. Military and civilian interests cannot be totally separated because, in certain cases, dynamic pressure from strong hurricanes may be comparable to that of nuclear blast effects. While the military applications requirement for no adverse effects on dash responsiveness and vehicle signature is of no interest in civilian applications, the weight and mobility requirements are significant to civil vehicles.

None of these requirements are germane to sited mobile homes. Military interest is primarily in blast-wave survivability, for which the shock loading differs significantly from that of storm winds, which are essentially steady state. However, since the element of drag loading is common to both, methods to improve survivability will also have common elements in both applications. The separation is made by setting the 30-kPa threshold, which corresponds to a particle velocity of about 60 m/sec in the shock front or a drag-force equivalent to about 130 mph for steady-state winds. With the large number of residents in mobile homes particularly at risk by displacement, translation, or overturn, a frequently used design objective for civil structures is survival in hurricane force winds of 120 mph. Survivability above the 30-kPa threshold is unique to military systems.

DATA SHEET 20.1. SYSTEM SURVIVABILITY AGAINST AIRBLAST

Developing Critical Technology Parameter	Methods for improving the survivability of aboveground fixed or land-mobile military systems, components, and materials (MSCM) against nuclear airblast (including thermal and dust effects) that are based on materials and data derived from tests.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes and mathematical algorithms that have been compared with nuclear detonations or simulations of a nuclear detonation for predicting the survivability of land-based assets. The models should include the following: EOS and material properties, mathematical relationships that have been specially designed to predict loads and/or responses of aboveground fixed or land-mobile systems, equipment, subassemblies, and other components. Of particular interest are those codes and algorithms that have been validated against computer-simulated or experimentally simulated nuclear environments for ground surface conditions/materials and terrain effects.
Major Commercial Applications	Buildings and certain mobile assets.
Affordability	Relatively inexpensive.

BACKGROUND

Because objects close to the nuclear blast most certainly will be destroyed, interest in blast-wave survivability is often concerned with hardening structures in the areas where structural reinforcement is feasible. With the exception of specific, specially hardened high-priority facilities, hardening is considered for those structures that exist at ranges well beyond the format of the Mach Stem. The dust lofting and increased dynamic pressure associated with the precursor enhance the potential damaging effects of this type of shock wave. Predicting precursor characteristics is difficult because of the complex interactions of the ground and lofted dust. Meaningful predictions require sophisticated computer models.

Airblast can also produce significant damage through the entrainment of particulates, which can produce erosion of critical components and materials. Test data are primarily for velocities above the 120-mph upper limit of potential civil interest. Even below this velocity, civil systems are generally not considered for dust-erosion protection. The only exception is the ingestion of static high-altitude dust by in-flight aircraft following a volcanic eruption. However, these evaluations are not carried out in tests in which the dust is levitated by an airblast, and the process of airblast dust levitation is unrelated to volcanic sources and distribution.

Thermal radiation from nuclear weapons is characterized by high thermal-energy density. When thermal radiation acts on a structure in conjunction with the airblast, the structures chance for survivability is decreased. Thus, data from simulations that replicate these combined effects are important for evaluating survivability.

Survival of military systems to nuclear ground shock is evaluated in tests in which significant effort is made to replicate nuclear ground-shock waveforms. Civil interest in ground shock is primarily limited to earthquake damage. Nuclear test data generally are not applicable because the wave shapes and time scales are significantly different and because the military structures of interest are located underground (missile silos, command posts). Earthquake damage is concerned with aboveground structures.

DATA SHEET 20.1. SHOCK-WAVE INSTRUMENTATION

Developing Critical Technology Parameter	Measure selective temporal features of nuclear-generated shock waves to an accuracy of < 0.1 ms. Examples include risetime, decay time, and duration of overpressure. Overpressure should be measured to < 0.1 atmospheres at standard temperature and pressure (STP).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial uses of explosives.
Affordability	Modest.

BACKGROUND

Low-altitude nuclear detonations produce shock waves that have unique risetimes, overpressures, decay times and undershoots related to the weapon yield and height of burst (HOB). Figure 20.1-6 shows the typical pressure waveform produced by a nuclear weapon. To harden structures adequately to nuclear pressure waveforms, the characteristics of the shock wave have to be defined accurately. This consideration becomes especially important when predictions for the nuclear detonations are made from scaled experiments. Measurement uncertainties in simulations using chemical explosives can often translate into larger uncertainties for the actual case.

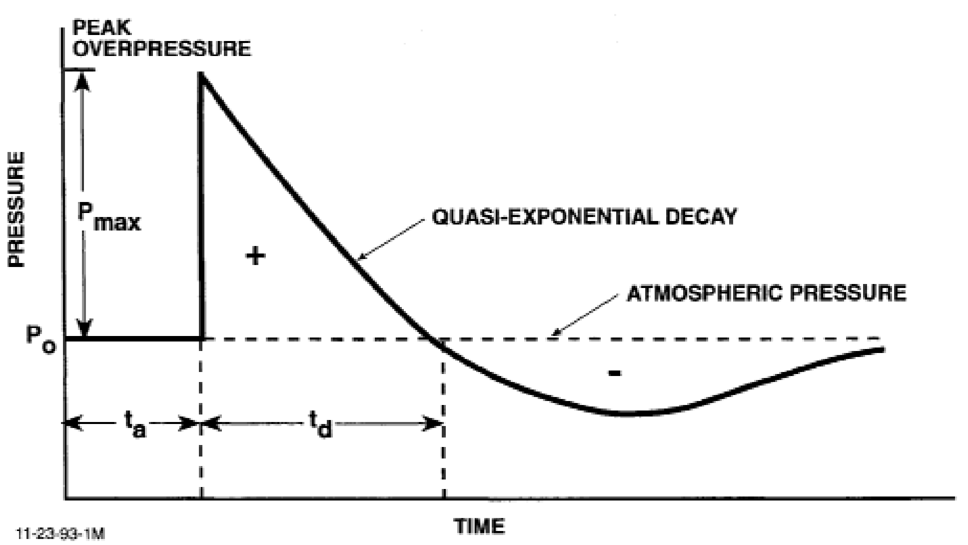


Figure 20.1-6. Typical Pressure-Time Curve for an Explosive Blast Wave (Source: Reference 1)

CITED REFERENCE

1. G.F. Kinney and K.J. Graham, *Explosive Shocks in Air*, Springer-Verlag, New York, 1985.

DATA SHEET 20.1. DYNAMIC PRESSURE GAUGE

Developing Critical Technology Parameter	Gauges or measurement techniques, such as a Greg gauge or Snob gauge, that can measure pressures with risetimes < 1 ms and duration < 5 sec and are specially designed or adapted to measure stagnation and/or total pressure in a highly transient dusty flow environment. Factors that must be taken into account include dust velocity, density, particle size distribution, particle velocity ≤ 1,000 m/sec, and density ≤ 50 mg/cc. These parameters are associated with a simulated nuclear weapon detonation over realistic ground surfaces.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

Low-altitude nuclear detonations produce shock waves that have unique risetimes, overpressures, decay times and undershoots related to the weapon yield and HOB. Figure 20.1-7 shows the typical pressure waveform produced by a nuclear weapon. To harden structures adequately against nuclear pressure waveforms, the characteristics of the shock wave have to be defined accurately. This consideration becomes especially important when predictions for the nuclear detonations are made from scaled experiments. Measurement uncertainties in simulations using chemical explosives can often translate into larger uncertainties for the actual case. For actual or simulated low-altitude detonations, energetic dust particles are lofted from the ground. These particles interact with the pressure gauge. This effect must be compensated for to deduce the real pressure produced by the detonation.

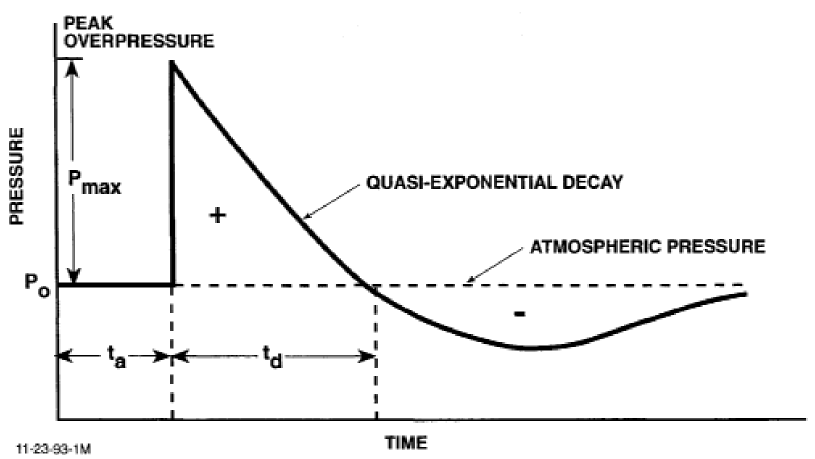


Figure 20.1-7. Typical Pressure-Time Curve for an Explosive Blast Wave (Source: Reference 1)

CITED REFERENCE

1. G.F. Kinney and K.J. Graham, *Explosive Shocks in Air*, Springer-Verlag, New York, 1985.

DATA SHEET 20.1. MINIATURIZED GAUGES

Developing Critical Technology Parameter	Miniaturized gauges having sensing elements properly sized and specially designed for measuring transient (i.e., not steady-state that a wind tunnel might produce) simulated nuclear environments or structural response tests at 1/20th (full-scale environment ≥ 1 kt yield) scale or smaller. For example, an airblast gauge with a 10-cm diameter sensing element (typically closer to 1 cm), which might provide adequate resolution for a full-scale test, would require a diameter of 1 mm to have adequate resolution for a 1/100th scale test.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Pressure measurements in small places.
Affordability	Modest.

BACKGROUND

Low-altitude nuclear detonations produce shock waves that have unique risetimes, overpressures, decay times and undershoots related to the weapon yield and HOB. Figure 20.1-8 shows the typical pressure waveform produced by a nuclear weapon. To harden structures adequately against nuclear pressure waveforms, the characteristics of the shock wave have to be defined accurately. This consideration becomes especially important when predictions for the nuclear detonations are made from scaled experiments. Measurement uncertainties in simulations using chemical explosives can often translate into larger uncertainties for the actual case. To measure pressure in a scaled experiment accurately, specially designed miniaturized gauges are required.

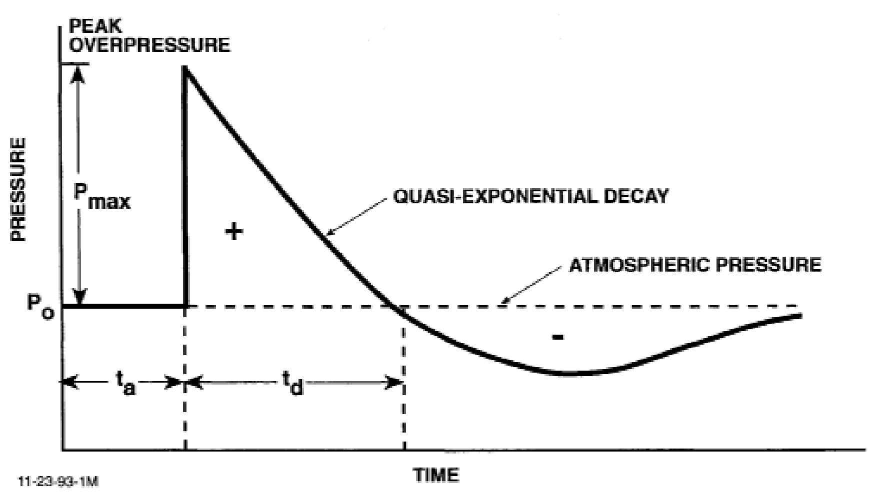


Figure 20.1-8. Typical Pressure-Time Curve for an Explosive Blast Wave (Source: Reference 1)

CITED REFERENCE

1. G.F. Kinney and K.J. Graham, *Explosive Shocks in Air*, Springer-Verlag, New York, 1985.

DATA SHEET 20.1. SHOCK TUBES

Developing Critical Technology Parameter	Shock tubes or other devices specially designed or modified to simulate the nonideal nuclear airblast environment. In particular, they must be capable of simulating a “pre-cursed front” or “decursed front” that would be produced by detonating a nuclear weapon over a real ground surface such as dust, snow, ice, vegetation, and so forth.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

Shock tubes are used to simulate two variants of normal shock waves, each of which is unique to the nuclear environment. One variant is a shock wave that carries a high density of entrained dust particles, resulting in a major deviation from mathematically ideal shocks and their pressure loading on targets. Such dust-loaded shock waves are unknown in other environments and are not used outside of nuclear weapons effects testing. A second variant is a nuclear weapon that emits significant amounts of thermal energy. When incident on some terrain, this energy can preheat the air immediately above the ground before airblast arrival.

Shock waves travel faster in heated air and more slowly in the cooler layers above it. The normal, nearly vertical shock front of the Mach Stem arrives more quickly than predicted for ambient conditions and with a slowly rising pressure pulse rather than the step-function of the classical shock. These are called “precursed shocks” or “decursed shocks” depending on whether the shock at the surface leads or (under some surface conditions) lags the free-air shock. Such thermal layers of differing sound velocity are frequently simulated in shock tubes and in high-explosive field tests by using bags filled with helium or other gases. Only the intense thermal radiation from a nuclear weapon is capable of producing this phenomenon naturally. Artificially created analogous environments using shock tubes can be used to applicable to simulate precursed or decursed shock waves.

DATA SHEET 20.1. DUST LOFTING

Developing Critical Technology Parameter	This technology is concerned with predicting the distortions in the surfaces caused by dust and debris in clouds produced by nuclear weapons. This issue is distinguished from naturally occurring dust because of the severity level and because of the significant difference in the size distribution of the dust and debris.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Mathematical models, algorithms, and related computer codes that predict cloud rise following a nuclear detonation. These codes include determining the particulate size, altitude, mass loading, and radioactivity as a function of weapon yield, HOB, and soil parameters. Of particular interest are those codes that have been validated against experimental data. Mathematical models, algorithms, and related computer codes that predict the degradation of the signal-to-noise ratio (SNR) of optical and infrared (IR) sensors to an accuracy < 3 dB because of dust and debris interactions with optical surfaces.
Major Commercial Applications	Effect of dust and debris clouds caused by volcanic eruptions.
Affordability	Modest.

BACKGROUND

Dust and debris lofting has been observed in nuclear airblasts that are close to the ground. The principal factors that determine the properties of the cloud are the weapon yield, HOB, and soil properties. When a nuclear weapon is detonated at a low altitude, the air is heated to very high temperatures, and significant levels of atmospheric turbulence are generated. Significant updrafts are developed, and these updrafts are capped with the familiar mushroom shape that is associated with low-altitude atmospheric detonations. The nuclear-generated shock wave forces ground matter into the upward air stream. This is the source of the dust and debris.

Once in the cloud, these particles are dragged upward by the air stream. The heavier particles tend to fall back to earth and the lighter ones are dragged to higher levels. At the upper regions of the cloud, the particles are churned by turbulence. The vigorous turbulence causes the lofted particles to hit each other occasionally. In some of these collisions, the particles stick together and produce a larger particle. This latter process is called coagulation.

There are theories that predict the size distribution of particles that are sucked into the cloud initially. Because different-size particles fall to the earth at different rates, are tossed around by turbulence differently, and occasionally coagulate, predicting the size and concentration as a function of position within the cloud after the upward draft and turbulence diminish is a complicated matter.

After cloud stabilization occurs, atmospheric transport occurs, bringing these particles into contact with aircraft. This contact occurs downwind.

Much theory is connected with atmospheric transport of nuclear dust and debris. Because of the large uncertainties connected with the shock-ground interaction and the description of turbulence within the cloud, prediction is best achieved when theoretical models are supplemented by experimental data.

DATA SHEET 20.1. GROUND-SHOCK PREDICTION

Developing Critical Technology Parameter	This technology is concerned with the effects of ground shock on surface-flush, shallow-buried, and deeply buried structures. The lower level of interest is a peak overpressure of 0.1 MPa for surface-flush and shallow-buried structures that extend from the surface to several meters below the surface. Surface-flush structures are typically missile silos. Shallow-buried structures are typically used for C3, personnel protection, and missile launch control. The environments of primary interest for each are consistent with peak overpressures from approximately 1 MPa to an upper limit of perhaps 1 GPa. For deeply buried structures, the environments of primary interest are from about 25 MPa to the nuclear weapon source.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes and related algorithms that have been validated against experiments and predict any of the following: airblast, ground shock, loads on flush-mounted, shallow-buried, or deeply buried structures that may include the effect of nonideal terrain.
Major Commercial Applications	Earthquake protection; mining engineering; planetary science.
Affordability	Inexpensive.

BACKGROUND

The three dominant components of ground shock are airblast-induced ground shock, direct-induced ground shock, and crater-related ground motion.

The airblast-induced ground shock, also called “air slap,” is the shock wave that is transmitted into the ground when an airblast is reflected at the earth’s surface. The direct-induced ground shock is produced principally by the KE of the weapon debris that forcefully strikes the earth. This results in a radially diverging shock wave resulting from the coupling of this energy to the surrounding ground. The crater-related ground shock is caused by the direct interaction of weapon debris and thermal radiation with the ground and relates to the growth of the crater. It develops more slowly than the direct-induced ground shock. The direct-induced and crater-related ground shocks are most effective when the burst is near the ground. Ground shock can penetrate to great depths and ranges and is capable of inflicting considerable damage to surface-flush, shallow-buried, and deeply buried structures.

Each of the ground shock components (airblast-induced ground shock, direct-induced ground shock, and crater-related ground shock) has a distinct pressure-time history, and their effects on a specific structure will be different.

DATA SHEET 20.1. NUCLEAR GROUND-SHOCK SIMULATOR

Developing Critical Technology Parameter	This technology is concerned with the effects of ground shock on surface-flush, shallow-buried, and deeply buried structures. The lower level of interest is a peak over-pressure of 0.1 MPa for surface-flush and shallow-buried structures that extend from the surface to several meters below the surface. Surface-flush structures are typically missile silos. Shallow-buried structures are typically used for C3, personnel protection, and missile launch control. The environments of primary interest for each are consistent with peak overpressures from approximately 1 MPa to an upper limit of perhaps 1 GPa. For deeply buried structures, the environments of primary interest are from about 25 MPa to the nuclear weapon source.
Critical Materials	Explosives or explosives mixed with inert materials (dilute explosives) specially designed for nuclear weapons simulation. All-weather materials that can protect RVs, launch vehicles, and aircraft against dust.
Unique Test, Production, Inspection Equipment	Instruments for measuring the effects resulting from stresses ≥ 10 MPa and gauges that measure stresses and strains in underground detonations.
Unique Software	Computer codes and related algorithms that support the development and use of nuclear ground-shock simulators. These codes and algorithms are required to predict any of the following: airblast, ground shock, and loads on flush-mounted, shallow-buried, or deeply buried structures that may include the effect of nonideal terrain.
Major Commercial Applications	Earthquake simulation; mining engineering.
Affordability	Moderately expensive.

BACKGROUND

The three dominant components of ground shock are airblast-induced ground shock, direct-induced ground shock, and crater-related ground motion.

The airblast-induced ground shock, also called “air slap,” is the shock wave that is transmitted into the ground when an airblast is reflected at the earth’s surface. The direct-induced ground shock is produced principally by the KE of the weapon debris that forcefully strikes the earth. This results in a radially diverging shock wave resulting from the coupling of this energy to the surrounding ground. The crater-related ground shock is caused by the direct interaction of weapon debris and thermal radiation with the ground and relates to the growth of the crater. It develops more slowly than the direct-induced ground shock. The direct-induced and crater-related ground shocks are most effective when the burst is near the ground. Ground shock can penetrate to great depths and ranges and is capable of inflicting considerable damage to surface-flush, shallow-buried, and deeply buried structures.

Each of the ground shock components (airblast-induced ground shock, direct-induced ground shock, and crater-related ground shock) has a distinct pressure-time history, and their effects on a specific structure will be different.

DATA SHEET 20.1. GROUND-SHOCK STRUCTURE SURVIVABILITY

Developing Critical Technology Parameter	Structures that can maintain their integrity when exposed to peak stresses of 25 to 500 MPa. This can be achieved by innovative uses of materials and designs. Techniques used to enhance structure survivability include shock-isolation techniques and related special materials; exotic high-strength concrete used for hardening silos; special ablative materials that can be used at the top of silos; and special foams, mechanical active isolators, and special reinforcing schemes using steel fibers.
Critical Materials	Specially designed materials and test data to increase the survivability of structures (including subassemblies, components, or parts) and their contents in nuclear ground-shock/motion environments.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Developing novel methods that enhance structure survivability. These include shock-isolation techniques and related special materials; exotic high-strength concrete used for hardening silos; special ablative materials that can be used at the top of silos; and special foams, mechanical active isolators, and special reinforcing schemes using steel fibers.
Major Commercial Applications	Commercial structures.
Affordability	Modest. Probably not much more expensive than standard practices for nonnuclear buildings.

BACKGROUND

The three dominant components of ground shock are airblast-induced ground shock, direct-induced ground shock, and crater-related ground motion.

The airblast-induced ground shock, also called “air slap,” is the shock wave that is transmitted into the ground when an airblast is reflected at the earth’s surface. The direct-induced ground shock is produced principally by the KE of the weapon debris that forcefully strikes the earth. This results in a radially diverging shock wave resulting from the coupling of this energy to the surrounding ground. The crater-related ground shock is caused by the direct interaction of weapon debris and thermal radiation with the ground and relates to the growth of the crater. It develops more slowly than the direct-induced ground shock. The direct-induced and crater-related ground shocks are most effective when the burst is near the ground. Ground shock can penetrate to great depths and ranges and is capable of inflicting considerable damage to surface-flush, shallow-buried, and deeply buried structures.

Each of the ground shock components (airblast-induced ground shock, direct-induced ground shock, and crater-related ground shock) has a distinct pressure-time history, and their effects on a specific structure will be different.

DATA SHEET 20.1. DISPOSABLE GROUND-SHOCK SIMULATION

Developing Critical Technology Parameter	The critical technology parameter is to develop one-time simulation techniques that can develop ground-shock environments ≥ 50 MPa. This requires that about 100 tons equivalent yield of TNT be coupled to the ground and provides the capability for evaluating structural effects for large systems. Full positive-phase ground shock/motions in rocks without degradation of the environment because of edge (relief) effects from the boundaries of the simulator.
Critical Materials	Explosives or explosives mixed with inert materials (dilute explosives) specially designed for nuclear weapons simulation.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Mining technology.
Affordability	Moderate to very expensive.

BACKGROUND

The three dominant components of ground shock are airblast-induced ground shock, direct-induced ground shock, and crater-related ground motion.

The airblast-induced ground shock, also called “air slap,” is the shock wave that is transmitted into the ground when an airblast is reflected at the earth’s surface. The direct-induced ground shock is produced principally by the KE of the weapon debris that forcefully strikes the earth. This results in a radially diverging shock wave resulting from the coupling of this energy to the surrounding ground. The crater-related ground shock is caused by the direct interaction of weapon debris and thermal radiation with the ground and relates to the growth of the crater. It develops more slowly than the direct-induced ground shock. The direct-induced and crater-related ground shocks are most effective when the burst is near the ground. Ground shock can penetrate to great depths and ranges and is capable of inflicting considerable damage to surface-flush, shallow-buried, and deeply buried structures.

Each of the ground shock components (airblast-induced ground shock, direct-induced ground shock, and crater-related ground shock) has a distinct pressure-time history, and their effects on a specific structure will be different.

DATA SHEET 20.1. GAUGE INSTALLATION

Developing Critical Technology Parameter	The critical technology is to reduce or eliminate the effects of the hole used for gauge installation when measuring stress in rock or cemented soils. The specific value of the parameter is not precisely defined since it depends on the application. For some applications, gauge installation must provide < 10-percent uncertainty in pressure and flow measurements beyond the hydrodynamic region (i.e., the region where the shear strength of the material is significant) and implement procedures for processing the data to correct for gauge inclusion effects, using specially designed rock-matching grout mixes or other gauge emplacement material.
Critical Materials	Specially designed rock-matching grout mixes or other gauge emplacement material.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Locations where accurate gauge installations are required.
Affordability	Relatively inexpensive.

BACKGROUND

This technology is common in general terms to most measurement systems. The fundamental idea is to ensure that inserting the measuring device does not alter the measurement itself. Gauge insertion technology is especially important for the nuclear case because the material surrounding the gauge may be stressed beyond its shear strength. This requires special techniques for processing the data to correct for gauge inclusion.

DATA SHEET 20.1. BLAST CHAMBERS

Developing Critical Technology Parameter	Blast chambers, explosively driven flyer plates, flash lamps, and so forth or other devices designed or specially designed to simulate the airblast, ground shock, or thermal environment predicted at a range from the nuclear weapon detonation equivalent to 50 MPa or to calibrate instrumentation packages dynamically (i.e., gauge, mount, placement method) in this regime in the media (rock or soil type) of interest. The main issue is that the more advanced versions of blast chambers, explosively driven flyer plates, and so forth developed since 1980 can simulate nuclear environments with pressures exceeding 50 MPa. This technology is unique to nuclear detonations and has no commercial application.
Critical Materials	High explosives.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

This technology is necessary for determining the survivability and hardness of surface-flush structures, shallow-buried structures, and deeply buried structures against the ground shock produced by a surface nuclear detonation. Simulation of ground shock using blast chambers provides a means of developing techniques that can harden surface-flush structures, shallow-buried structures, and deeply buried structures against a nuclear surface burst.

DATA SHEET 20.1. PARTICLE VELOCITY GAUGES

Developing Critical Technology Parameter	Particle velocity gauges, mounting hardware, signal conditioning, and other associated hardware, based on mutual inductance (current induced on a conductor moving in a magnetic field) capable of measuring particle velocities associated with peak soil/rock stresses > 100 MPa resulting from a simulated nuclear-weapon detonation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate to expensive.

BACKGROUND

This technology is concerned with assessing the survivability and hardness of surface-flush structures, shallow-buried structures, and deeply buried structures by simulation using aboveground high explosives or an underground nuclear detonation.

DATA SHEET 20.1. UNDERGROUND TEST (UGT) ENVIRONMENT GAUGES

Developing Critical Technology Parameter	Gauges specially designed to determine the environments that an underground nuclear detonation produces by directly measuring any of the following effects: shear stress or shear and normal stresses between a structure and the surrounding media and displacement, strain, or pore water pressure of geological materials.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

This technology is concerned with assessing the survivability and hardness of surface-flush structures, shallow-buried structures, and deeply buried structures by simulation using aboveground high explosives or an underground nuclear detonation.

DATA SHEET 20.1. UNDERWATER NUCLEAR SHOCK PREDICTION

Developing Critical Technology Parameter	Overpressures > 100 psi and having impulse sufficient to degrade the operational capability of sea-based assets resulting from an underwater nuclear detonation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Validated computer codes and algorithms that predict overpressure and impulse on surface ships and submarines caused by nuclear-produced underwater detonations out to ranges where the pressures fall to 100 psi.
Major Commercial Applications	None identified.
Affordability	Inexpensive.

BACKGROUND

An underwater nuclear explosion releases large amounts of thermal energy and nuclear radiation that are absorbed within a few feet of the explosion. This intense energy deposition creates a hot gas bubble that is formed by the vaporization of the water and expands rapidly. A shock wave similar to that created by a nuclear explosion in air is formed. Because the shock-wave generation is similar in both cases, scaling relationships, which play a large role in understanding and simulating an airburst, are also relevant for simulating underwater explosions.

A considerable amount of basic scientific information addresses underwater nuclear explosions and the development of computer codes to handle these problems in stratified media.

DATA SHEET 20.1. UNDERWATER NUCLEAR SHOCK SIMULATION

Developing Critical Technology Parameter	Overpressures > 100 psi and having impulse sufficient to degrade the operational capability of sea-based assets resulting from an underwater nuclear detonation.
Critical Materials	Conventional high-explosive charges engineered to simulate underwater nuclear detonations [e.g., tapered charges (long, slender charges consisting of a series of truncated cones of various angles and diameters)] dilute explosives, line charges, and sheet charges to simulate various nuclear pressure-time profiles using data taken from actual tests.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Validated computer codes and algorithms that predict overpressure and impulse on surface ships and submarines caused by nuclear-produced underwater detonations out to ranges where the pressures fall to 100 psi.
Major Commercial Applications	None identified.
Affordability	Moderately expensive.

BACKGROUND

An underwater nuclear explosion releases large amounts of thermal energy and nuclear radiation that are absorbed within a few feet of the explosion. This intense energy deposition creates a hot gas bubble that is formed by the vaporization of the water and expands rapidly. A shock wave similar to that created by a nuclear explosion in air is formed. Because the shock-wave generation is similar in both cases, scaling relationships, which play a large role in understanding and simulating an airburst, are also relevant for simulating underwater explosions.

The amount of hydrostatic pre-load greatly affects the structural response of submarines to underwater shock. The depths of inland test facilities can allow testing only to a small fraction of the operating depths of modern submarines. Testing at deep depths typically involves open-ocean test operations, with extensive costs for personnel, rigging, and test resources (i.e., test ships), and requires consideration of environmental concerns. Inducing a hydrostatic pre-load in the vicinity of structural models without significantly altering the desired loading function allows simplified and cost-effective testing at inland test sites.

Using large high-explosive charges to simulate nuclear effects is not always feasible for two reasons. First, the pressure in the shock wave from the large high-explosive charge still decays far more rapidly than typical nuclear yields of interest. As such, it may not fully "envelop" large structures such as ships and submarines. This alters the damage conditions expected of nuclear environments. Second, the use of large high-explosive charges is restricted environmentally. Inland test facilities are not large enough to use large high-explosive charges, and at-sea tests are becoming prohibitively expensive and are restricted environmentally. These conditions are often true even for small-scale model tests. Capabilities to simulate nuclear shock environments with low yields of high explosives alleviate these problems.

DATA SHEET 20.1. SHAPED CHARGES

Developing Critical Technology Parameter	Conventional high-explosive charges engineered to simulate underwater nuclear detonations [e.g., tapered charges (long, slender charges consisting of a series of truncated cones of various angles and diameters)] dilute explosives, line charges, and sheet charges to simulate various nuclear pressure-time profiles using data taken from actual tests.
Critical Materials	Dilute explosives.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Excavation.
Affordability	Moderate.

BACKGROUND

Since the 1963 atmospheric test ban, no underwater nuclear tests have been performed. Using large high-explosive charges to simulate nuclear effects is not always feasible for two reasons. First, the pressure in the shock wave from the large high-explosive charge still decays far more rapidly than typical nuclear yields of interest. As such, it may not fully “envelop” large structures such as ships and submarines. This alters the damage conditions expected of nuclear environments. Second, the use of large high-explosive charges is restricted environmentally. Inland test facilities are not large enough to use large high-explosive charges, and at-sea tests are becoming prohibitively expensive and are restricted environmentally. These conditions are often true even for small-scale model tests. Capabilities to simulate nuclear shock environments with low yields of high explosives alleviate these problems.

DATA SHEET 20.1. STRUCTURAL COATING

Developing Critical Technology Parameter	Structural coatings of synthetic and/or composite materials used to harden the external surface of ships and submarines against the shock wave produced by an underwater nuclear detonation.
Critical Materials	Synthetic and/or composite materials used to harden surfaces against shock waves.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial vessels that are subject to impact.
Affordability	Wide range: moderate to expensive.

BACKGROUND

Thick coatings are already applied to modern submarines to reduce acoustic signatures. Currently, little is understood about the effect of these coatings on shock wave loading. These coatings possibly could be optimized for acoustic performance and shock protection. A shock-mitigating coating could lower accelerations into sensitive internal equipment and allow for increased overall survivability of the submarine or, perhaps, contribute to reduced costs in “hardening” the equipment against underwater shock.

DATA SHEET 20.1. SHOCK ISOLATION

Developing Critical Technology Parameter	Shock-isolation systems that are used to harden ships and submarines against the shock wave produced by an underwater nuclear detonation and that have been developed using simulated underwater nuclear detonations.
Critical Materials	Materials that absorb shock and can be integrated into the internal structure of vessels.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Mathematical models, algorithms, and related computer codes that predict shock waves on complex internal structures.
Major Commercial Applications	Commercial vessels that are subject to impact.
Affordability	Wide range: moderate to expensive.

BACKGROUND

Modern combat ships and submarines undergo an extensive process to "harden" all critical equipment against conventional and nuclear shock. This equipment must satisfy stringent testing requirements to qualify for shipboard use. However, this testing for conventional and nuclear programs results in specialized military specification (MIL-SPEC) equipment designs that are expensive and often do not include state-of-the-art technology improvements.

Developing and using advanced shock-mitigating systems for internal equipment would facilitate the hardening of critical equipment, perhaps even allowing the use of commercial off-the-shelf (COTS) equipment on combat vessels. The ships could quickly accommodate new hardware (i.e., electronics that undergo rapid advances in technology).

In the event that current survivability standards need to be increased in the future, a combination of equipment hardening *and* advanced shock-mitigating concepts would be required. By implementing these procedures now, the potential future cost savings would be significant.

DATA SHEET 20.1. THERMOMECHANICAL SHOCK (TMS) PREDICTION

Developing Critical Technology Parameter	Generate time history (1- to 100-ns pulse duration) of soft-X-ray-induced shock wave on space platforms.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes that predict the time development of TMS on space systems caused by X-rays from a high-altitude nuclear detonation. These codes model the time and space incident X-ray deposition, subsequent material phase change, shock generation and propagation, lateral stress development, spallation, and structural deformation and fracturing as a function of time.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

A nuclear detonation produces copious amounts of X-rays. For a high-altitude nuclear detonation, the X-rays travel from the location of the detonation to the space platform with minimal attenuation because the air density at high altitudes is very low. These X-rays strike the surface and are absorbed in a thin layer. The impulse created by this effect generates a shock wave that travels through the space platform and causes physical damage to the structure. Predicting this phenomenon is unique and requires the integration of specific dynamic models for X-ray energy deposition, material phase change, shock generation and propagation, lateral stress development, spallation, and structural deformation and fracturing.

DATA SHEET 20.1. THERMOMECHANICAL SHOCK (TMS) SIMULATOR

Developing Critical Technology Parameter	Generate time history (1- to 100-ns pulse duration) of soft-X-ray-induced shock wave on space platforms.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Optical measuring systems that exhibit < 10 mm per meter change in lateral or longitudinal dimensions when exposed to levels of X-ray-generated pressures and impulses necessary to degrade the operational effectiveness of space assets.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

A nuclear detonation produces copious amounts of X-rays. For a high-altitude nuclear detonation, the X-rays travel from the location of the detonation to the space platform with minimal attenuation because the air density at high altitudes is very low. These X-rays strike the surface and are absorbed in a thin layer. The impulse created by this effect generates a shock wave that travels through the space platform and causes physical damage to the structure.

Our systems have to be hardened against the high-altitude X-ray threat. Simulating the TMS using an X-ray source provides a key element in designing structures that can withstand the nuclear X-ray threat.

DATA SHEET 20.1. X-RAY EFFECTS REDUCTION

Developing Critical Technology Parameter	Manufacturing methods for fabricating structures that exhibit < 1 mm per meter change in longitudinal dimension when exposed to X-ray fluences and related spectra characteristics of a nuclear detonation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

A nuclear detonation produces copious amounts of X-rays. For a high-altitude nuclear detonation, the X-rays travel from the location of the detonation to the space platform with minimal attenuation because the air density at high altitudes is very low. These X-rays strike the surface and are absorbed in a thin layer. The impulse created by this effect generates a shock wave that travels through the space platform and causes physical damage to the structure.

Our systems have to be hardened against the high-altitude X-ray threat. Manufacturing methods used to construct materials that are resistant to thermal expansion are important in developing systems that can survive the X-ray threat.

DATA SHEET 20.1. SHOCK-WAVE MEASUREMENT

Developing Critical Technology Parameter	Test equipment for measuring the shock-wave characteristics of materials and structures when exposed to X-ray fluences and spectra characteristics of a nuclear detonation. This requires an X-ray simulator and specially designed instrumentation capable of making fast transient measurements of parameters such as pressure, temperature, stress, velocity, density, and phase state.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

A nuclear detonation produces copious amounts of X-rays. For a high-altitude nuclear detonation, the X-rays travel from the location of the detonation to the space platform with minimal attenuation because the air density at high altitudes is very low. These X-rays strike the surface and are absorbed in a thin layer. The impulse created by this effect generates a shock wave that travels through the space platform and causes physical damage to the structure.

Our systems have to be hardened against the high-altitude X-ray threat. This is accomplished via nuclear underground testing or testing of systems in an X-ray simulator. Measuring the X-ray-induced shock wave in these facilities provides a key element in designing structures that can withstand the nuclear X-ray threat.

DATA SHEET 20.1. COMPOSITE MATERIALS

Developing Critical Technology Parameter	The key materials technology relates to composite materials that are lightweight and strong and, combined with their resistance to X-rays, are appropriate for aerospace systems. These materials should have minimal displacement and distortion when exposed to large X-ray flux from a nuclear weapon and should resist spallation at the surface. Any level of increased resistance to distortion by X-rays is valuable.
Critical Materials	Lightweight and strong materials that resist distortion caused by heating by X-rays.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Applications that require minimal distortion during heating.
Affordability	Very expensive.

BACKGROUND

A nuclear detonation produces copious amounts of X-rays. For a high-altitude nuclear detonation, the X-rays travel from the location of the detonation to the space platform with minimal attenuation because the air density at high altitudes is very low. These X-rays strike the surface and are absorbed in a thin layer. The impulse created by this effect generates a shock wave that travels through the space platform and causes physical damage to the structure. These effects can be mitigated by the choice of materials that absorb the X-rays.

DATA SHEET 20.1. MATERIAL RESPONSE TO PARTICLES

Developing Critical Technology Parameter	This technology refers to the degradation of optical and IR systems because of distortions in the surfaces produced by particles of a nuclear cloud. Mitigating the effects of hypervelocity impact of particles with velocities > 1 km/sec to objects that are of military significance. This includes ablation and erosion studies for windscreens, cruise missile engines, aircraft engines, and so forth. The environments refer to those generated by a nuclear detonation and not by other means. The software evaluates the response of military systems to this environment and has no commercial application. Codes and algorithms for predicting the degradation of the SNR of optical and IR sensors to < 3 dB because of the effect of nuclear cloud.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Codes and algorithms for simulating nuclear detonations that can predict the material response of materials to impacting solid and/or liquid particles with impact velocities > 1 km/sec and that include the following features: smoke, soot, and debris from industrial plants and urban environments. Codes and algorithms that predict the degradation of optical and IR systems because of distortions in the surfaces produced by particles of a nuclear cloud. The unique feature of these codes is their use of dust particle sizes that pertain to a nuclear cloud (as distinguished from naturally occurring dust) and the use of related experimental data.
Major Commercial Applications	Protection of windows and engines on aircraft, and optical and IR sensors that must operate in windy and dusty environments.
Affordability	Expensive.

BACKGROUND

Figure 20.1-9 shows the generation of a nuclear dust cloud. This cloud consists of the dust lofted in the characteristic mushroom formation because of the direct interaction of the airblast with the ground and of the dust swept up off the ground surface by the airblast. Both components of dust are transported downwind by the ambient atmospheric winds.

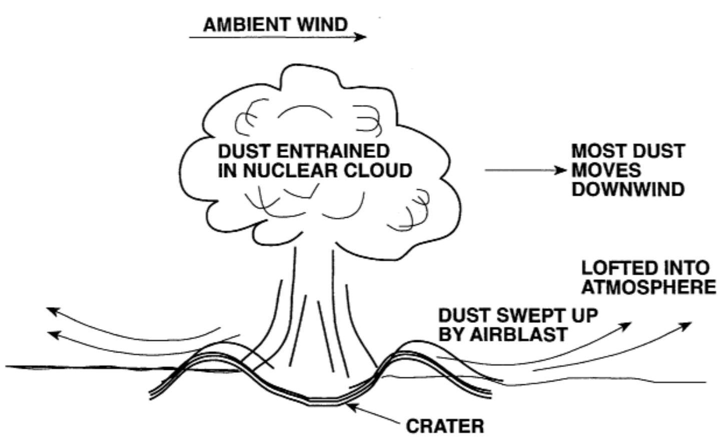


Figure 20.1-9. Generation of Nuclear Dust Cloud

Because dust clouds cause aircraft windshields and engines to erode, they are an important consideration for aircraft. Predicting the amount of dust lofted into the air through crater development and then swept into the air by the winds associated with the airburst is an important challenge. For crater development, we must account for the particle size distribution in the soil, the effects of turbulent coagulation in the rising vortices of the mushroom cloud, condensation, and so forth.

DATA SHEET 20.1. SPACECRAFT STRUCTURAL RESPONSE

Developing Critical Technology Parameter	Codes and algorithms that have been compared with simulations of nuclear tests and can predict the mechanical and structural response of missile/spacecraft structures from weapon-generated X-rays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	These codes are unique to the nuclear survivability of space systems because they model the initial X-ray deposition (energy and penetration depth as a function of time); the subsequent material phase change, shock generation and propagation; lateral stress development; spallation; and structural deformation and fracturing as a function of time. The early-time response is generated by X-rays from a nuclear weapon.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

A nuclear detonation produces copious amounts of X-rays. For a high-altitude nuclear detonation, the X-rays travel from the location of the detonation to the space platform with minimal attenuation because the air density at high altitudes is very low. These X-rays strike the surface and are absorbed in a thin layer. The impulse created by this effect generates a shock wave that travels through the space platform and causes physical damage to the structure. Predicting this phenomenon is unique and requires the integration of specific dynamic models for X-ray energy deposition, material phase change, shock generation and propagation, lateral stress development, spallation, and structural deformation and fracturing.

DATA SHEET 20.1. X-RAY PROTECTIVE COATINGS

Developing Critical Technology Parameter	Materials that are capable of absorbing X-rays produced by a nuclear detonation without generating the high temperatures and high pressures required for development of a shock wave.
Critical Materials	Protective coatings against X-rays to reduce the shock-wave pressure. Materials for these coatings are characterized by low atomic number (Z), low effective Gruniessen coefficient, and high melting temperature and include boron nitride, alumina, and titanium carbide.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

A nuclear detonation produces copious amounts of X-rays. For a high-altitude nuclear detonation, the X-rays travel from the location of the detonation to the space platform with minimal attenuation because the air density at high altitudes is very low. These X-rays strike the surface and are absorbed in a thin layer. The impulse created by this effect generates a shock wave that travels through the space platform and causes physical damage to the structure.

SECTION 20.2—HARD TARGET PENETRATION

Highlights

- KEWs cause damage by destroying structures and/or vaporizing materials. The extent of damage depends on the target's material characteristics and the energy transfer to the target.
- Testing to determine lethality can be performed at low velocities and low-projectile masses. At high velocities, costs and the availability of sensors and detection technology prohibit effective live-fire testing, especially in space. At velocities over 2 km/sec, especially for KEW with masses over a kilogram, computer simulations have to be used to determine lethality and weapon effects.
- Physics-based computer codes require relatively long running times but are capable of producing high-fidelity results.
- Empirically based codes run faster than physics-based codes but are not as generally applicable and are of lower fidelity.
- Knowledge of material properties at extreme thermodynamic conditions (high temperature and pressure) is required for weapons effects simulations.
- Scaled-down testing is possible under some conditions.
- High-velocity launchers are available over a limited range of velocities and masses. These range from $v \sim 1$ km/sec and $m < 10$ kg to $v < 8$ km/sec and $m < 0.5$ kg.

OVERVIEW

The technologies in this section address methods for simulating and evaluating the effects of PWs on surface, space, and underground targets. These weapons destroy targets by penetrating, perforating, and rupturing the impacted material. The high incident KE of these PWs produces shock waves and plastic deformation in the target. The extremely large pressures and shearing forces associated with the shock waves generated during the projectile-target interaction are intended to exceed the latter's elastic limit. Depending on the host material, this can result in permanent cratering, vaporization, deformation, erosion, melting, perforation, and even ionization of the target.

This section emphasizes the initial impact/shock/penetration effects of penetrators. Pyrophoric effects add to the damage of internal volumes by creating overpressures and by igniting other materials. Some efforts have been made (especially in the late 1980s) to characterize such effects.

Specific technologies include the effects of PWs on surface, buried, and space targets. Laboratory techniques for assessing the effectiveness of these penetration weapons are also discussed, as are the theoretical models and computer codes that form the basis of predicting the effectiveness of this class of weapons. With few exceptions, the technologies addressed in this section have not reached their potential capability.

BACKGROUND

The effects of projectile penetration on materials are of great interest to the military community, from a defensive and an offensive perspective. The contest between better projectiles and more effective armor has been a principal motif in military history. In an attempt to build more effective weapons, the understanding of the interaction between the projectile and the target has been the goal of designers, builders, and testers. This understanding is usually achieved through a combination of experimental work and computer simulations. The U.S. planners, however, have reached a point where experimental techniques are no longer adequate to examine the parameter space of interest to weapon designers, except for using hardware similar to that being studied.

The continued interest in hypervelocity projectiles that have velocities of 5 to 10 km/sec has forced researchers and decision-makers to rely more heavily on computer simulations because the cost and inherent difficulties of conducting the experiments required to compile the data are prohibitive. Also, for some cases of interest, equipment is not even available to generate the appropriate conditions of high KE. Consequently, reliance on computer codes has been growing, and the development of physics-based codes has been supported. Researchers feel that these codes, which are based on sound physical principles, will provide accurate predictions of lethality under diverse conditions.

In addition to computational approaches, subscale experiments using lower-mass projectiles at high velocities are being supported to obtain needed benchmarks to validate current and future computer codes. The validity of computational approaches and the benefits to be obtained from subscale experiments continue to be investigated.

The impact conditions are determined by the guidance system characteristics and can usually be parametrized as experimental conditions. On the other hand, the material properties are basic to the simulation and need to be determined. Figure 20.2-1 shows the uncertainty in the material properties of a simple material, copper. Imagine the difficulties that will be encountered when the properties of more complex materials under such extreme conditions are required.

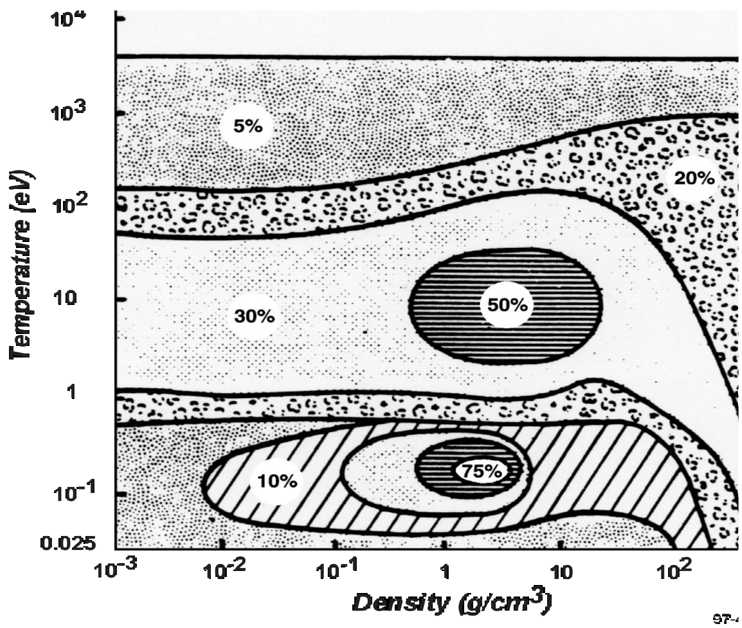


Figure 20.2-1. Uncertainties in the EOS of Copper

The problem of high velocity impact testing and lethality assessment is difficult because the velocities required are suborbital-to-orbital and the masses involved are large. The combination of velocities and masses exceeds any collision energy we are capable of generating on the ground in a test or experiment. Yet, to gain confidence in the operational effectiveness of systems, we have to obtain information on the interactions.

To overcome this problem and obtain the required information, two different approaches have been taken: computer modeling and subscale testing. The advantage of computer modeling is that high-resolution temperature, density, and pressure profiles can be made available to the analyst and weapons designer. (High-resolution data are not likely to be obtained from experiments.) However, the computational approach is limited by computer speed and memory and by the lack of knowledge of appropriate material properties at extreme conditions. Subscale testing is complicated by the requirement to scale the physics. Relating scaled experiments to full-scale conditions is difficult because of the nonlinear nature of some of the phenomena being examined.

Another approach that could be used involves full-scale testing of subsections of the larger system combined with computer modeling. This approach—sectional testing with simulation—would include taking into account the interactions of the subsections forming the total system. The results of the testing could be included in a computer model dealing with a full-scale interaction. The computer code would be the glue that would model the interactions between the subsystems.

The computational method is a hybrid between a full-scale hydrocode run and an engineering code run. The advantage of this approach would be that the material properties would not have to be calculated and the non-linearity in scaling would be avoided. The subsystems could be made small and light enough to permit experimental testing and, at the same time, complex enough to provide substantial information that is difficult to model. This hybrid approach is a new concept that needs to be explored more fully.

LIST OF TECHNOLOGY DATA SHEETS
20.2. HARD TARGET PENETRATION

DATA SHEET 20.2. PENETRATING WEAPON (PW) EFFECTS ON SURFACE TARGETS

Developing Critical Technology Parameter	Critical offensive technologies include the development of hypervelocity projectiles, such as long-rod PWs, shaped charges, and explosively formed penetrators (EFPs), that can penetrate through known forms of protective armor. These are the offensive capabilities for which survivability must be established. On the defensive side, the critical technologies include armor that can protect land surface targets against long-rod PWs, which have a velocity > 1.8 km/sec; shaped charge jets, which are capable of penetrating rolled homogeneous armor (RHA) > 10 charge diameters; and EFPs, which are self-forming, explosive, energy-derived ballistic projectiles capable of producing projectile lengths > 1 charge diameter.
Critical Materials	Complex assemblies of materials consisting of layers of metals, composites foams, ceramics, adhesives, and high explosives tailored to protect against KE attack; very dense materials of special constructions that can resist fragmentation and absorb shock wave; RHA.
Unique Test, Production, Inspection Equipment	Projectile launchers capable of imparting velocities exceeding 1.8 km/sec in laboratory-scale facilities; test targets, physical models, and instrumentation uniquely suited for hypervelocity impact (HVI) assessments.
Unique Software	Validated computer programs and algorithms for evaluating and optimizing reactive armor configurations; validated computer programs and algorithms, including material models for assessing the KEW effects on targets.
Major Commercial Applications	Body armor for law enforcement; personal protection; automobile armoring; safe deposit boxes; bomb containment systems; aircraft protection against bird strikes; design of protective structures for civil defense; and so forth.
Affordability	Highly variable depending on application.

BACKGROUND

The simulation technologies of this section, which consist of analysis and software use and development supported by testing, provide a quantitative basis for establishing the survivability of targets. These technologies address methods for testing, simulating, and evaluating the effects of PWs on surface targets such as tanks (and other armored vehicles), trucks, and missile transporters and launchers. These PWs destroy targets by rupturing and, to some extent, even vaporizing the impacted material. The high incident KE per square meter of these PWs produces intense shock waves in the target. The extremely large pressures and shearing forces associated with the shock waves generated during the projectile-target interaction are intended to exceed the target's elastic limit. Depending on the host material, this can result in permanent damage caused by plastic flow, ablation, vaporization, cratering, and even ionization of the target. With few exceptions, these technologies have not reached their potential capability.

The technologies covered in this data sheet have dual-use applications. They include, for example, body armor for law enforcement, bomb containment systems, aircraft protection against bird strikes, and survivability of satellites against micrometeorites.

DATA SHEET 20.2. PENETRATING WEAPON (PW) EFFECTS ON SPACE TARGETS

Developing Critical Technology Parameter	Orbiting fragment masses in the range of 1g < m < 100 g for any material/phase; impulse mechanisms capable of delivering > 1 ktap against satellites and impact energy > 1 MJ against RVs and missiles; EOS at high strain rate (material dependent). Knowledge of this technology Improves an adversary's capability to evaluate the survivability of satellites, RVs, and missiles against KE projectiles and fragments.
Critical Materials	Aluminum; kelvar; composites; nextel.
Unique Test, Production, Inspection Equipment	Two-stage light gas gun (LGG) that launches different shaped projectiles at > 7 km/sec, inhibited shape charge launcher that launches 1 g aluminum projectiles at 11.5 km/sec; three-stage gas gun that uses flyer plate to deliver 0.7g at 10 km/sec or 0.4 g at 15 km/sec.
Unique Software	Validated computer programs and algorithms for employing redundancy to achieve system survivability; computer codes to calculate damage produced by fragments of different shapes and sizes.
Major Commercial Applications	Survivability of commercial satellites and the space station against micrometeorites and space debris using shield design and redundancy; development of insensitive explosives.
Affordability	None identified.

BACKGROUND

The simulation technologies of this section, which consist of analysis and software use and development supported by testing, provide a quantitative basis for establishing the survivability of targets. These technologies address methods for testing, simulating, and evaluating the effects of PWs on space targets such as RVs, missiles, and satellites. These PWs destroy targets by rupturing and, to some extent, even vaporizing the impacted material. The high incident KE per square meter of these PWs produces intense shock waves in the target. The extremely large pressures and shearing forces associated with the shock waves generated during the projectile-target interaction are intended to exceed the target's elastic limit. Depending on the host material, this can result in permanent damage caused by plastic flow, ablation, vaporization, cratering, and even ionization of the target. With few exceptions, these technologies have not reached their potential capability.

DATA SHEET 20.2. PENETRATING WEAPON (PW) EFFECTS ON BURIED TARGETS

Developing Critical Technology Parameter	Depth and payload capability for penetrating into or close to a target buried more than 2 m; depth at which new technologies, such as improved delay fuzing, boosted penetration, and high-density bodies, are required.
Critical Materials	Boulder fields on surface; reinforced concrete slabs on bunkers; soil; penetration-resistant armor on bunkers; high-density case materials.
Unique Test, Production, Inspection Equipment	Test facilities for simulating multilayer ground/bunker penetrating configurations under battlefield conditions.
Unique Software	Validated software programs that describe projectile penetration through the ground.
Major Commercial Applications	Safe storage facilities against natural disasters.
Affordability	None identified.

BACKGROUND

The simulation technologies of this section, which consist of analysis and software use and development supported by testing, provide a quantitative basis for establishing the survivability of targets. These technologies address methods for testing, simulating, and evaluating the effects of PWs on buried targets. These PWs destroy targets by rupturing and, to some extent, even vaporizing the impacted material. The high incident KE per square meter of these PWs produces intense shock waves in the target. The extremely large pressures and shearing forces associated with the shock waves generated during the projectile-target interaction are intended to exceed the target's elastic limit. Depending on the host material, this can result in permanent damage caused by plastic flow, ablation, vaporization, cratering, and even ionization of the target. With few exceptions, these technologies have not reached their potential capability.

DATA SHEET 20.2. DATA TESTING OF HYPERVELOCITY IMPACT (HVI) EFFECTS

Developing Critical Technology Parameter	Facilities for testing HVI effects at velocities > 1.8 km/sec for long-rod penetrators; impulse > 1 ktap at velocities > 7 km/sec against satellite mock-ups; energy > 1 MJ against RVs and missiles; penetration through ground against buried bunkers.
Critical Materials	Applique armor; reactive armor; ceramics; composites; titanium alloys; aluminum; kelvar; steel; explosive materials.
Unique Test, Production, Inspection Equipment	Launchers that produce projectiles with velocities > 1.8 km/sec for ground targets and fragments traveling > 7 km/sec for satellites and RVs; EFP; debris shields; boulder fields; reinforced concrete; armor-type bunker slabs; pressure and temperature sensors for measuring impact induced phenomena; readout instrumentation for data retrieval from impact tests.
Unique Software	Software for data analysis and modeling of impact tests.
Major Commercial Applications	Body armor; bomb containment; space platform survivability; buried storage facilities; protective structure design.
Affordability	None identified.

BACKGROUND

The simulation technologies of this section, which consist of analysis and software use and development supported by testing, provide a quantitative basis for establishing the survivability of targets. Technologies in this section address methods for testing, simulating, and evaluating the effects of PWs on buried targets. These PWs destroy targets by rupturing and, to some extent, even vaporizing the impacted material. The high incident KE per square meter of these PWs produces intense shock waves in the target. The extremely large pressures and shearing forces associated with the shock waves generated during the projectile-target interaction are intended to exceed the target's elastic limit. Depending on the host material, this can result in permanent damage caused by plastic flow, ablation, vaporization, cratering, and even ionization of the target. With few exceptions, these technologies have not reached their potential capability.

The technologies covered in this data sheet have dual-use applications. They include, for example, body armor for law enforcement, bomb containment systems, and survivability of satellites against micrometeorites.

DATA SHEET 20.2. COMPUTER SHOCK PHENOMENA CODES

Developing Critical Technology Parameter	Validated computer codes and algorithms that include EOS models at high strain rates for predicting hypervelocity impact against solid/complex targets, armor, fragments against space targets, and penetration against buried objects with uncertainties < 10 percent. **Physics-Based Codes.** Two types of physics-based codes are used widely in the Department of Defense (DoD) community for lethality analyses: the standard hydrocode and the smoothed particle hydrodynamics (SPH) code. The standard hydrocode requires a grid to carry out the calculation. The grid can be Eulerian or Lagrangian or a combination of the two. The SPH code does not require a grid. It models the material as a collection of particles that move according to hydrodynamic equations. **Engineering Codes.** The engineering codes are similar to expert systems. The expert-system approach uses information from analytical models, hydrocodes, experimental data, and intuitive reasoning to simulate hypervelocity systems behavior. The algorithms used in these codes cannot be derived from physical theory alone. **Comparisons of Codes.** The hydrocodes can provide high-fidelity calculations of complex systems but they require long run times. The engineering codes are fast and can be used to obtain statistics but with pseudo realistic or questionable models.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Validated Lagrange-Eulerian codes and algorithms that predict the performance of PWs against targets and include material models; input/output (I/O) signals of sensors in single/multiple impact warheads, fractionation, vaporization, melt.
Unique Software	None identified.
Major Commercial Applications	Body armor; bomb containment; space platform survivability; buried storage facilities.
Affordability	None identified.

BACKGROUND

In large part, offensive and defensive military interests have driven the physics of impact. The contest between faster projectiles and stronger armor has been the principal motif in military history. In an attempt to build more effective weapons, understanding the interaction between the projectile and the target has been the goal of designers, builders, and testers. This understanding is usually achieved through a combination of experimental work and computer simulations. However, we have reached a point where experimental techniques are inadequate to examine the parameter space of interest to weapon designers and policy planners. Thus, current test facilities are often not capable of reproducing the end velocities and extracting all the data from tests that are required for an adequate understanding of lethality.

The simulation technologies of this section, which consist of testing, analysis, and software use and development, provide a quantitative basis for establishing the survivability of targets. These technologies address methods for testing, simulating, and evaluating the effects of PWs on buried targets. These PWs destroy targets by rupturing the impacted material. The high incident KE per square meter of these PWs produces intense shock waves in the target. The extremely large pressures and shearing forces associated with the shock waves generated during the projectile-target interaction are intended to exceed the target's elastic limit. Depending on the host material, this can result in permanent damage caused by plastic flow, ablation, vaporization, cratering, and even ionization of the target. Also, PWs that attack surface targets could conceivably be modified to attack underground targets (e.g., bunkers containing chemical or biological weapons) relevant to weapons of mass destruction (WMD). With few exceptions, these technologies have not reached their potential capability.

Computer codes designed to deal with shock phenomena have a long history of validation and verification, initially on simple scenarios that can be easily compared with test results (see Figures 20.2-2, 20.2-3, and 20.2-4) before they are applied with confidence to more complex but also more useful scenarios (see Figure 20.2-5).

In Figure 20.2-2, we compare the results from a simulation using CTH and SPHINX[2] for a penetration of a tungsten rod of a semi-infinite steel wall. The split image on the left gives the equal stress profiles (left) and the material distortion (right). The center shows a SPHINX result identifying the material distortion, and, on the right, the pressure is displayed. Figure 20.2-5 shows a more complex scenario with a fragmented missile impacting on a target with multiple canisters. This impact is not as readily tested for detailed analysis, and computer simulations are needed to provide the required understanding of damage caused under various conditions of velocity, geometry, and impact point.

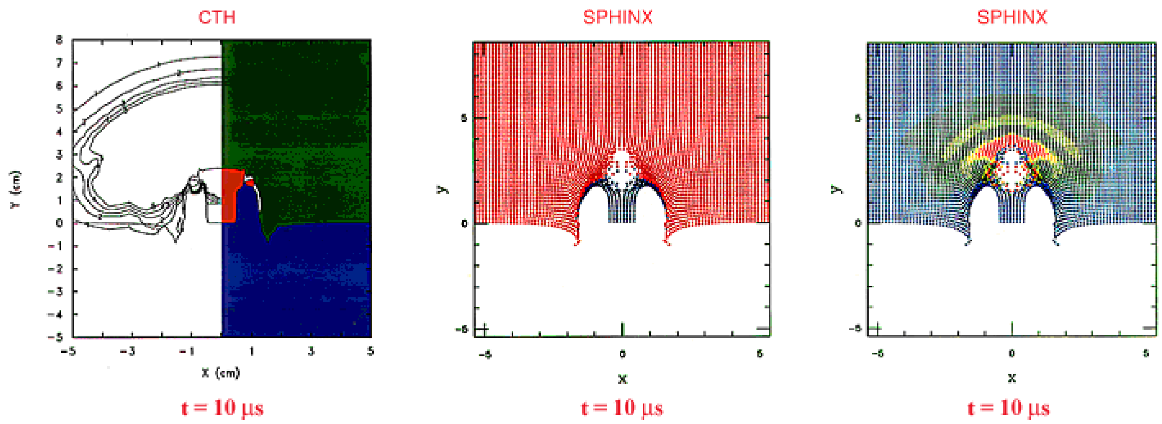


Figure 20.2-2. Penetration of a Wall by a Circular Rod

Note for Figure 20.2-2: *Results from CTH and SPHINX runs are shown for comparison.*

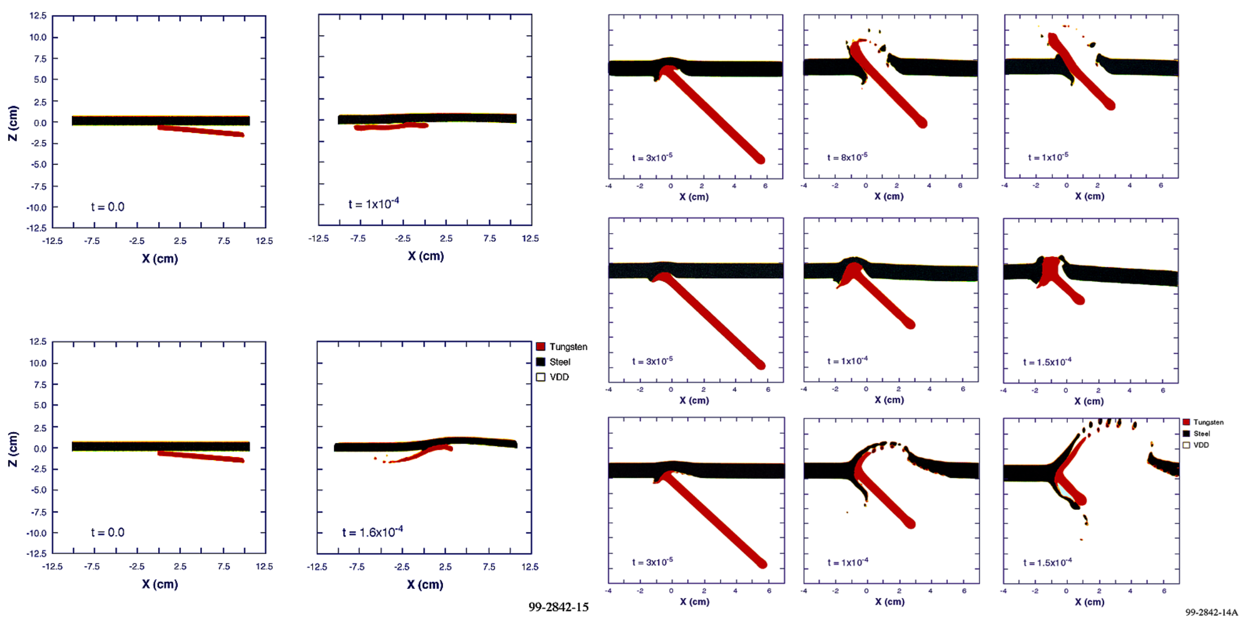


Figure 20.2-3. A Study of the Penetration of a Moving Target (Wall) by Thin Rods (Flechettes) at Different Obliquities

Note for Figure 20.2-3. *Shallow angle of penetration (left), with target stationary (top) and moving (bottom). Penetration at 45 degrees with target stationary and moving to right and left.*

---

2 CTH is a Eulerian hydrocode, and SPHINX is an SPH code.

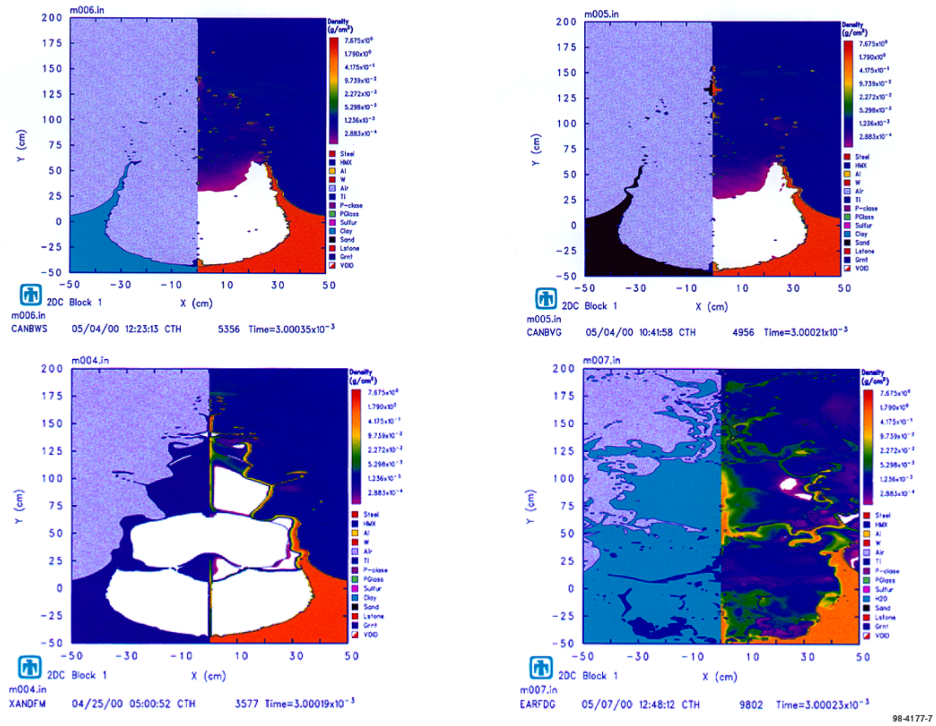


**Figure 20.2-4. Simulation of a Mine Exploding in Various Media:
Sand (Top Left) and Soil (Top Right), Quartz (Bottom Left), and Water (Bottom Right)**

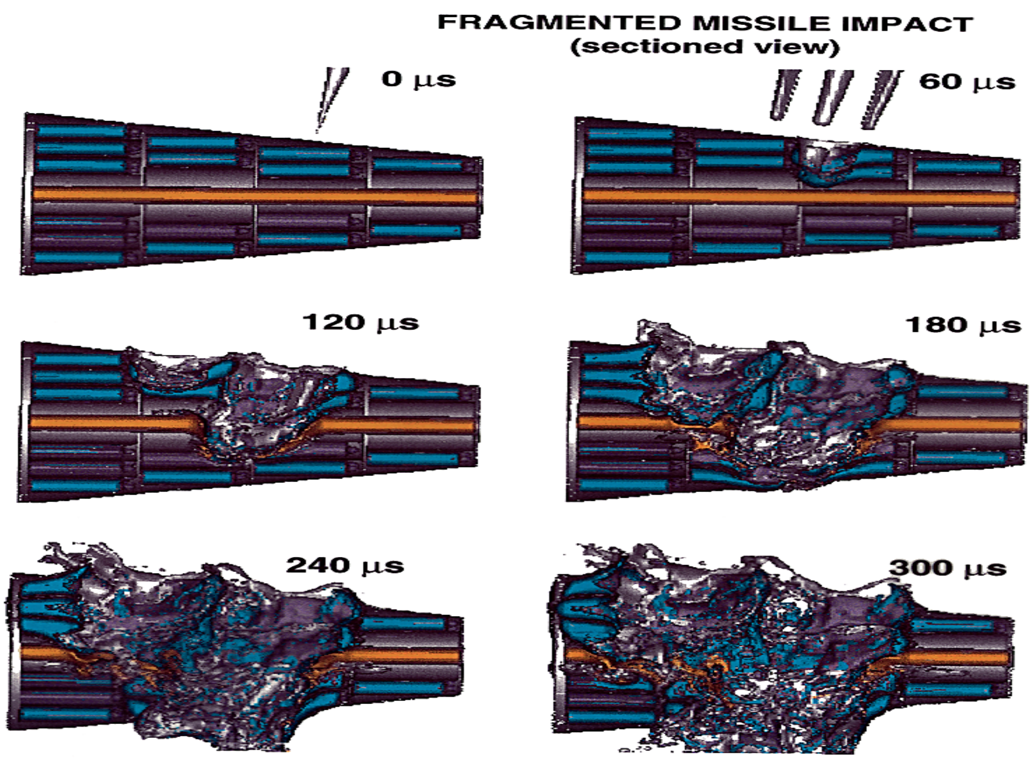


**Figure 20.2-5. Penetration of a Target Consisting of Multiple Canisters
by a Fragmented Missile (Source: L. Schwalbe, LANL)**

DATA SHEET 20.2. SATELLITE DEBRIS SHIELD AND REMOVAL

Developing Critical Technology Parameter	Protective shields against orbiting fragment masses in a range of $0.01 < m < 100$ g. Shields to be used for protection against any material/phase and impulse mechanisms capable of delivering > 1 ktap against satellites. EOS under high strain rates (material dependent); debris shields that weigh < 10 g/cm^2. Improves adversary's capability to evaluate the survivability of satellites against co-orbiting fragments; provides new approaches to destroy debris or reduce the damage from debris. Ground-based laser (GBL) orbital debris removal concept.
Critical Materials	Aluminum; kelvar; composites; spectra; nextel.
Unique Test, Production, Inspection Equipment	Two-stage LGG that launches different shaped projectiles at > 7 km/sec; inhibited shape charge launcher that launches 1-g aluminum projectiles at 11.5 km/sec; three-stage gas gun that uses flyer plate to deliver 0.7 g at 10 km/sec or 0.4 g at 15 km/sec.
Unique Software	Validated computer models that predict the effects of space fragments on debris shields and the survivability of space platforms based on redundancy of components.
Major Commercial Applications	Survivability of commercial satellites and the space station against micrometeorites and space debris using shield design and redundancy; development of insensitive explosives.
Affordability	None identified.

BACKGROUND

The material in space that can damage to our space hardware comes basically from two sources: space debris and orbital debris. Space debris can be characterized as solar flux, lunar flux, and interplanetary flux, according to the source of the material. Orbital debris is a result of man-made space activity, accidental collisions, and unintentional explosions. Space activity contributes about 300 objects annually—even after the natural sweeping processes of drag removal and disintegration in the atmosphere.

Space Debris

This category includes particles with masses from 10^{-17} grams (comets) to 10^{16} grams (meteors), with bulk mass densities from 0.2 to 2 gm/cm^3. These extraterrestial "particles" or meteoroids travel from 12 to 72 km/sec and can cause extensive damage upon collision.

Orbital Debris

Man has been contributing orbital debris since the beginning of space flights. For this discussion, we will consider two size classes (less than 10 cm and greater than 10 cm) of orbital debris and three regions of space in which the debris predominantly exists [Low Earth Orbit (LEO), less than 5,500-km altitude; Middle Earth Orbit (MEO), between 5,500 km and 35,863 km; and Geosynchronous Earth Orbit (GEO) for objects flying about 35,863 km]. Objects in LEO have a period (one rotation around the earth) of about 225 min, and those in GEO have a period of about 24 hrs.

The particle distribution is not uniform in altitude. In LEO, the particle distribution peaks between 800-km altitude and 1500-km altitude. The estimated debris population shows 7,000 objects in orbit greater than 10 cm in size, 17,500 objects in orbit between 1 cm and 10 cm in size, and 3,524,500 objects less than 1 cm in size.

Damage From Debris

In a general way, the effect of debris impact on structures depends on the velocity and mass of the impacting particle. For example at 10 km/sec, an object less than or about 0.01-cm average dimension can cause surface damage, an object from 0.01 cm to 1.0 cm can cause significant impact damage, and an object 1 cm or larger can cause catastrophic damage. These size groups have a lot of overlap, but at least they provide a guideline to the extent of the effects expected in such collisions.

How often do such collisions occur? It has been estimated that a surface with an area of 5,000 m^2 at an altitude of 500 km experienced one impact every 20 years in 1988 and, in 2010, will experience an impact every 2.5 years. This increase is cause by the increased buildup of debris in space. Similarly, a surface with an area of 40 m^2 at 800 km in altitude experienced only one impact every 950 years but, in 2010, will experience one impact every 110 years.

If we want keep going into space, we have to reduce this density of orbital debris and provide some robust shielding for the structures that we send into space.

DATA SHEET 20.2. MOVING CHARGE EFFECTS

Developing Critical Technology Parameter	Penetrating missiles that travel at velocities > 200 m/sec, carry explosives, and are detonated at a predetermined time after impact destroy the target (or are more lethal) in a way much greater than that expected from the combined kinetic and explosive energies. Synergistic effects that are not well understood seem to be involved. There is not much test data or experimental results on which to base a theory. There is, however, fragmentary information about tests and the history of testing and about collected fragments from testing, but not a sufficiently developed theory to build the pieces of information into a model.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Two-stage LGG that launches different shaped projectiles at > 1 km/sec; full-scale testing facility with X-ray shadowgraph capability; pressure sensors and strain gauges; rocket sled test track capable of moving 10 kg masses at 1–3 km/sec.
Unique Software	Validated computer models that predict the effects of fragments on debris shields; physics-based hydrocodes and finite element structural codes that have the capability to model explosives. Specifically for the moving charge problem, the simulation of explosive material as it is implemented in these codes has to be evaluated.
Major Commercial Applications	Design of bomb shelters, bunkers, and government or commercial buildings or other public buildings.
Affordability	None identified.

BACKGROUND

A moving missile that has an explosive warhead should produce more damage than either a missile alone or the explosive alone. This is expected because, to a first approximation, the explosive chemical energy is added to the KE of the missile, thus increasing the damage to the target. What is not obvious is whether a synergistic effect increases the damage above and beyond the simple additive energy effect. What is also not obvious is how the coupling to the target is accomplished for different velocities and for structures of different complexities. The simple addition of energies may not completely explain all the observed phenomena.

The open literature provides limited experimental test results and limited applications of simple shock-wave theory to targets in moving media. No realistic theory includes blast effects, shock-wave phenomena, and fragmentation effects in the same model.

Theoretical studies also concentrate on direct blast effects and shock propagation in open regions, not through complex structures. Complex material properties were introduced into the analysis indirectly by some investigators.

SECTION 20.3—THERMAL RADIATION

Highlights

- The thermal flash generated by a nuclear weapon in the megaton class is able to ignite structures at distances greater than the nuclear blast wave. Ignition of wood and so forth takes place at an energy density of about 5 cal/cm^2, while many modern structures can withstand overpressures of at least a few pounds per square inch (psi).
- Nuclear-weapon-generated thermal radiation can produce flash burns on unprotected human beings—but at distances. Simple precautions can greatly reduce injuries.
- Thermal radiation from a nuclear weapon can adversely affect optical sensors in the IR through the ultraviolet (UV) regions of the electromagnetic spectrum.
- The simulation of thermal radiation in the atmosphere requires taking into account the effects of absorption.
- High-temperature blackbody radiation sources are used for simulation of the nuclear thermal radiation.

OVERVIEW

The significantly militarily critical technologies associated with thermal radiation are those caused by nuclear detonations and nonnuclear high-temperature blackbody radiation sources. The technologies in this section address the prediction and interpretation of the thermal radiation output of a nuclear detonation, the response of systems to the thermal radiation, and the methods for simulating the thermal radiation.

The thermal flash from a low-altitude nuclear detonation can ignite structures and can produce flash burns on unprotected humans. The blast wave generated by a low-altitude nuclear detonation occurs in conjunction with the nuclear thermal flash. Since thermal radiation weakens structures, the thermal flash makes the blast wave more effective in damaging structures.

Thermal radiation from nuclear detonations or nonnuclear sources can adversely affect sensors operating in the IR through the UV regions of the electromagnetic spectrum. This occurs when the intensity of the radiation incident on the sensor is well above the design limits.

The technologies associated with the simulation of nuclear and nonnuclear thermal effects are very important. Most simulations require the development of equivalent blackbody radiation sources that operate around 3,000 K. Lasers can be used to simulate the effects on sensors and other optical components. Solar energy sources or chemical sources can be used for system-level testing.

BACKGROUND

When weapons in the 1- to 200-kt region are used against structures commonly found in the West, blast effects are likely to predominate. Larger weapons will have the ability to start fires at distances far greater than that at which they can inflict significant blast damage. Films of tests conducted in Nevada in the 1950s confirm that at the range where wood-frame houses can be ignited by lower-yield weapons, the buildings are blown down seconds later by the blast wave. On the other hand, structures that survive the blast generally do not ignite from the thermal pulse. Tests conducted in the Pacific using megaton-class weapons show the opposite effect. Secondary fires started by broken gas mains, electrical short circuits, and so forth are not considered here.

Blast and shock effects fall off roughly as the inverse cube of the distance from a nuclear explosion, while thermal radiation decays only as the inverse square of the distance from the detonation. Thus, weapons in the megaton class and above are primarily incendiary weapons—able to start fires and cause other thermal damage at distances well beyond the radius at which they can topple buildings or overturn armored vehicles.

The effect of thermal radiation on unprotected human beings could be very serious, producing flesh burns over large areas of the body. However, as the Hiroshima and Nagasaki bombings demonstrated, once the victim is beyond the radius at which light-colored fabrics are directly ignited, even simple precautions can greatly reduce the extent and seriousness of the thermal injuries.

A structure's response to the thermal pulse from a nuclear weapon depends upon several different factors. The structure's intrinsic composition plays a key role. For example, wood, masonry, or concrete will respond very differently to a thermal pulse, particularly if this pulse is concurrent with a blast wave. The type of exterior paint is also an important property, especially its thermal radiation reflection coefficient. Other factors include the transparency of any windows facing the burst; the type, texture, and composition of roofing; and even the presence or absence of awnings and shades.

LIST OF TECHNOLOGY DATA SHEETS
20.3. THERMAL RADIATION

DATA SHEET 20.3. THERMAL RADIATION CHEMICAL SOURCES

Developing Critical Technology Parameter	3,000-K-equivalent blackbody radiation sources with pulse length > 1 sec that can provide a flux > 7 cal/cm^2-sec to test objects with volumes > 100 ft^3.
Critical Materials	Liquid oxygen; powdered aluminum.
Unique Test, Production, Inspection Equipment	Movable asymptotic calorimeters for measuring thermal flux; cameras with spectral resolution < 0.25 nm, digital sampling rate > 120/sec, and 10-bit resolution.
Unique Software	No special commercial software is required for power control.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

The thermal flash from a low-altitude nuclear detonation can ignite structures and can produce flash burns on unprotected humans. The blast wave generated by a low-altitude nuclear detonation occurs in conjunction with the nuclear thermal flash. Since thermal radiation weakens structures, the thermal flash makes the blast wave more effective in damaging structures. Thermal radiation from nuclear detonations or nonnuclear sources can adversely affect sensors operating in the IR through the UV regions of the electromagnetic spectrum. This occurs when the intensity of the radiation incident on the sensor is well above the design limits.

The technologies associated with the simulation of nuclear and nonnuclear thermal effects are very important. Most simulations require the development of equivalent blackbody radiation sources that operate around 3,000 K. Lasers can be used to simulate the effects on sensors and other optical components. Solar energy sources or chemical sources can be used for system-level testing.

Certain chemical reactions can reproduce some of the desired thermal radiation effects. The principal reason for using chemical reactions to reproduce thermal radiation effects is the low cost of operation. Chemical reactions have an inherent upper temperature limit that is well suited for thermal radiation simulation. The chemical reaction is most useful when the surface temperature of the reaction “flame” has an equivalent blackbody temperature greater than 3,000 K.

DATA SHEET 20.3. SOLAR POWER TOWER

Developing Critical Technology Parameter	Heliostats and receivers that produce 3,000-K-equivalent blackbody radiation sources and provide ≥ 5 MW total thermal power, peak fluxes ≥ 260 W/cm^2, illuminate targets as large as 27 m^2, and simulate thermal nuclear transient in second range.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Instrumentation, including photometers and flux gauges that can accurately measure incident flux densities in the tens-of-W/cm^2 range. (Temperature and flux are inferred from power density measurement.)
Unique Software	No special commercial software is required for power control. Programming effort is challenging but straightforward.
Major Commercial Applications	None identified.
Affordability	Moderately expensive.

BACKGROUND

The thermal flash from a low-altitude nuclear detonation can ignite structures and can produce flash burns on unprotected humans. The blast wave generated by a low-altitude nuclear detonation occurs in conjunction with the nuclear thermal flash. Since thermal radiation weakens structures, the thermal flash makes the blast wave more effective in damaging structures. Thermal radiation from nuclear detonations or nonnuclear sources can adversely affect sensors operating in the IR through the UV regions of the electromagnetic spectrum. This occurs when the intensity of the radiation incident on the sensor is well above the design limits.

The technologies associated with the simulation of nuclear and nonnuclear thermal effects are very important. Most simulations require the development of equivalent blackbody radiation sources that operate around 3,000 K. Lasers can be used to simulate the effects on sensors and other optical components. Solar energy sources or chemical sources can be used for system-level testing. Figure 20.3-1 shows the solar power tower located at Sandia National Laboratory (SNL). This tower is used to simulate the nuclear thermal flash.

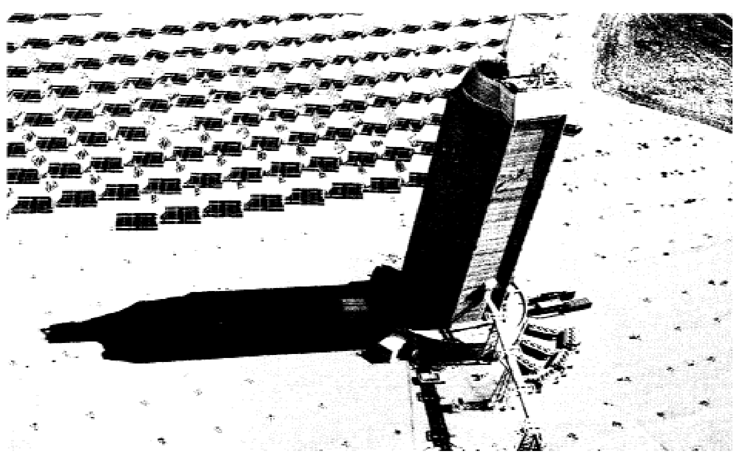


Figure 20.3-1. Solar Power Tower Located at SNL (Source: Reference 1)

CITED REFERENCE

1. “National Solar Thermal Test Facility,” Brochure published by Sandia National Laboratories.

DATA SHEET 20.3. SOLAR PARABOLIC DISH

Developing Critical Technology Parameter	Parabolic dish that generates solar thermal power by tracking the sun, provides ≥ 75 kW total thermal power and peak flux ≥ 1,500 W/cm^2 over a 15-in. diameter circular area, and can control pulse duration in millisecond range.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Instrumentation including photometers and flux gauges that can accurately measure incident flux densities in the tens-of-W/cm^2 range. (Temperature and flux are inferred from power density measurement.)
Unique Software	No special commercial software is required for power control. Programming effort is challenging but straightforward.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

The thermal flash from a low-altitude nuclear detonation can ignite structures and can produce flash burns on unprotected humans. The blast wave generated by a low-altitude nuclear detonation occurs in conjunction with the nuclear thermal flash. Since thermal radiation weakens structures, the thermal flash makes the blast wave more effective in damaging structures. Thermal radiation from nuclear detonations or nonnuclear sources can adversely affect sensors operating in the IR through the UV regions of the electromagnetic spectrum. This occurs when the intensity of the radiation incident on the sensor is well above the design limits.

The technologies associated with the simulation of nuclear and nonnuclear thermal effects are very important. Most simulations require the development of equivalent blackbody radiation sources that operate around 3,000 K. Lasers can be used to simulate the effects on sensors and other optical components. Solar energy sources or chemical sources can be used for system-level testing. Figure 20.3-2 shows a point-focus parabolic dish located at SNL. Its potential to simulate the nuclear flash remains to be explored.

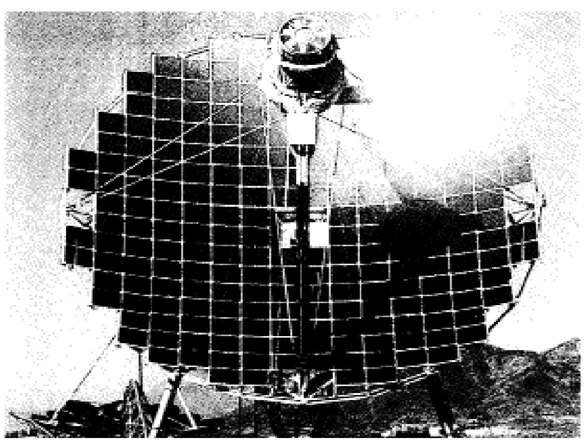


Figure 20.3-2. Point-Focus Parabolic Dish Located at SNL (Source: Reference 1)

CITED REFERENCE

1. "National Solar Thermal Test Facility," Brochure published by Sandia National Laboratories.

DATA SHEET 20.3. SOLAR FURNACE SYSTEMS

Developing Critical Technology Parameter	Heliostat that tracks and directs sunlight into parabolic dish, can provide greater than total thermal power and peak flux ≥ 400 W/cm^2, and can control power to simulate nuclear thermal transients.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Instrumentation, including photometers and flux gauges that can accurately measure incident flux densities in the tens of W/cm^2 range. (Temperature and flux are inferred from power density measurement.)
Unique Software	No special commercial software is required for power control. Programming effort is challenging but straightforward.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

The thermal flash from a low-altitude nuclear detonation can ignite structures and can produce flash burns on unprotected humans. The blast wave generated by a low-altitude nuclear detonation occurs in conjunction with the nuclear thermal flash. Since thermal radiation weakens structures, the thermal flash makes the blast wave more effective in damaging structures. Thermal radiation from nuclear detonations or nonnuclear sources can adversely affect sensors operating in the IR through the UV regions of the electromagnetic spectrum. This occurs when the intensity of the radiation incident on the sensor is well above the design limits.

The technologies associated with the simulation of nuclear and nonnuclear thermal effects are very important. Most simulations require the development of equivalent blackbody radiation sources that operate around 3,000 K. Lasers can be used to simulate the effects on sensors and other optical components. Solar energy sources or chemical sources can be used for system-level testing. Figure 20.3-3 is a picture of a solar furnace located at SNL.

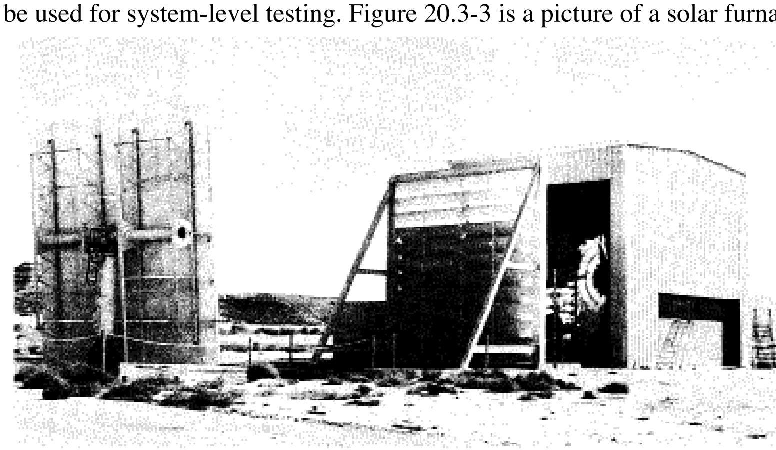


Figure 20.3-3. Solar Furnace Located at SNL (Source: Reference 1)

CITED REFERENCE

1. "National Solar Thermal Test Facility," Brochure published by Sandia National Laboratories.

DATA SHEET 20.3. THERMAL EFFECTS SIMULATOR: INFRARED (IR) DETECTORS

Developing Critical Technology Parameter	Peak energy density from 1 to 10^3 J/cm^2; peak power density from 10^3 to 10^6 W/cm^2; laser irradiation pulses from 10^{-7} to 1 sec; uncertainty-of-damage threshold < 35 percent.
Critical Materials	Photovoltaic detectors: HgCdTe, PbSnTe; pyroelectric detectors: TGS, SBN; thin-film photoconductors: PbS, PbSe; bulk HgCdTe.
Unique Test, Production, Inspection Equipment	Laboratory lasers that have the following capabilities: peak energy density from 1 to 10^3 J/cm^2, peak power density from 10^3 to 10^6 W/cm^2, and pulse width from 10^{-7} to 1 sec.
Unique Software	None identified.
Major Commercial Applications	IR detectors.
Affordability	Moderate.

BACKGROUND

Thermal radiation from nuclear detonations or nonnuclear sources can adversely affect sensors operating in the IR through the UV regions of the electromagnetic spectrum. This occurs when the intensity of the radiation incident on the sensor is well above the design limits. Figure 20.3-4 shows a cross-sectional view of a representative PbS photoconductor under uniform laser irradiation.

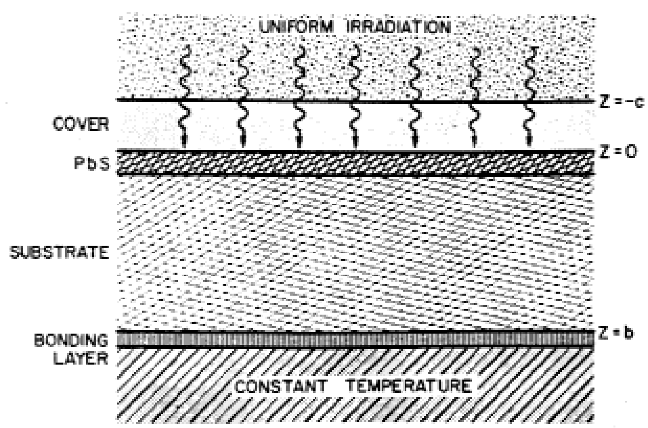


Figure 20.3-4. Cross-Sectional View of a Representative PbS Photoconductor (Source: Reference 1)

Vaporization or melting causes irreversible damage in photoconductors, cracking caused by thermal stresses can damage pyroelectric detectors, and junction degradation causes damage to photodiodes. In addition to damage, thermal loading in photoconductive detectors can cause signal degradation and lead to system performance degradation. Thermal models that describe thermal loading and damage must be capable of handling thermally resistive bonding layers and include the temperature dependence of materials.

The onset of damage is defined as 10-percent irreversible damage. The uncertainty-of-damage threshold is estimated at 35 percent. A key requirement in evaluating detector performance is determining the relationship between incident energy density (or, equivalently, incident power density) as a function of pulse duration. Figure 20.3-5 shows the threshold between power density and irradiation time for PbSe photoconductors.

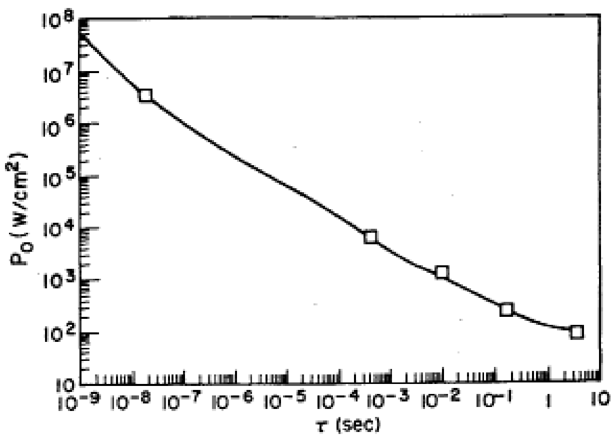


Figure 20.3-5. Threshold Values of Power Density for Onset of Permanent Damage of PbSe Photoconductors as a Function of Irradiation Time (Source: Reference 1)

Note for Figure 20.3-5: *The squares represent experimental data.*

CITED REFERENCE

1. M. Kruer et al., "Thermal Analysis of Laser Damage in Thin-Film Photoconductors," *J. Appl. Phys.,* Vol. 47, No. 7, July 1976.

DATA SHEET 20.3. THERMAL EFFECTS SIMULATOR: OPTICAL SEMICONDUCTOR

Developing Critical Technology Parameter	Pulse length between 10^{-9} to 10^{-4} sec; power density from 10^5 to 10^8 W/cm^2.
Critical Materials	Ge, Si, InSb, GaAs, SiGa, SiAs, InAs, InGaSb, PbSnSe, $LiTaO_3$.
Unique Test, Production, Inspection Equipment	Laboratory lasers having following range of capability: pulse length between 10^{-9} and 10^{-4} sec and power density from 10^5 to 10^8 W/cm^2.
Unique Software	None identified.
Major Commercial Applications	Laser annealing; optical semiconductors.
Affordability	Moderate.

BACKGROUND

Thermal radiation from nuclear detonations or nonnuclear sources can adversely affect sensors operating in the IR through the UV regions of the electromagnetic spectrum. This occurs when the intensity of the radiation incident on the sensor is well above the design limits. Figure 20.3-6 shows a cross-sectional view of a representative PbS photoconductor under uniform laser irradiation.

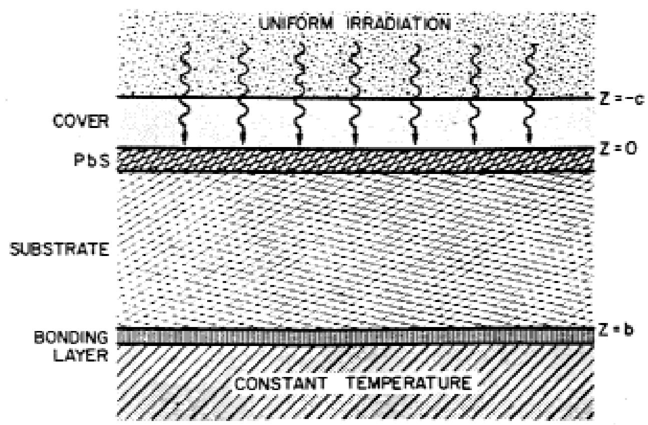


Figure 20.3-6. Cross-Sectional View of a Representative PbS Photoconductor (Source: Reference 1)

Rigorous theories of laser heating effects in optical semiconductors are complex. They must accurately model optical and carrier transport and heat transport. The basic model includes coupled diffusion equations for temperature and excess carrier density. Of particular interest is the manner in which the transport properties vary with temperature. This renders the transport equations nonlinear. Important nonlinear processes include two-photon absorption, free-carrier absorption, and dynamic Burstein shift.

A major parameter in heating and damage is the incident radiation's depth of penetration. The energy density thresholds for damage decrease with increasing pulse length. For example, in germanium, the damage threshold goes from 10^8 to 10^5 W/cm^2 as the pulse length goes from 10^{-9} to 10^{-4} sec.

CITED REFERENCE

1. M. Kruer et al., "Thermal Analysis of Laser Damage in Thin-Film Photoconductors," *J. Appl. Phys.,* Vol. 47, No. 7, July 1976.

DATA SHEET 20.3. COLD X-RAY SIMULATOR: X-RAY MACHINES

Note: *The material on this datasheet is identical with that on a datasheet entitled* ***DATA SHEET III-20.4. COLD X-RAY EFFECTS SIMULATION****. We include this material here to cover the discussion of methods for simulating thermal-generated effects on structures. The reader is referred to Section 20.4 for a more complete discussion of cold X-Ray effects and a more extensive reference list.*

Developing Critical Technology Parameter	X-rays under 15 keV produced by Z-pinches or other devices that can be used to approximate the cold X-ray spectrum produced by a high-altitude nuclear detonation; sources > 40 kJ using 1- to 10-keV X-rays and > 5 kJ using 5- to 20-keV X-rays in under 100 ns over an area > 1 cm^2; debris mitigation techniques; X-ray optic components with reflectivity > 20 percent; methods for collecting and focusing X-rays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

Cold X-rays, defined as those that have energies under 15 keV, are especially damaging to space systems. The coupling of the weapon debris to the atmosphere in a high-altitude detonation creates these cold X-rays, which are absorbed on the surface of the space platforms and can generate shock waves in the systems. These shock waves can cause structural damage: TMS, thermostructural response (TSR), and other malfunctions to optical sensor systems.

Copious amounts of cold X-rays can be simulated by using a plasma radiation source such as a Z-pinch, an ion source, or, in some cases, a flash X-ray (FXR) source. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation).

DATA SHEET 20.3. COLD X-RAY SIMULATOR: MAGNETICALLY DRIVEN FLYER PLATE

Developing Critical Technology Parameter	Magnetically driven flyer plates that simulate at the surface of space platforms thermally generated pressures as high as 10 kbar, and impulses as low as ~ 5 ktap (500 Pa-s).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Pulsed-power system for magnetic field.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Magnetically driven flyer plates can produce high pressure loading at low-to-moderate impulses. Simulating cold X-Rays often requires peak pressures of a few tens of gigapascals, with impulses of a few pascal-seconds. This requirement is met using magnetically driven flyer plates. These magnetic pressure techniques work best when the target is smooth and relatively simple in shape. The concept is eminently suitable when the structural response (in this case, the pressure pulse) is applied nearly uniformly over the entire surface and when the structural response times are an important factor. A good example of the use of magnetically driven flyer plates is determining the response of conical RVs.

The energy required for the magnetically driven flyer plate ranges from about 50 to 500 kJ. The source of this energy is a capacitor bank. The voltage on the bank of capacitors is about 50 kV. Opposing currents are created between the conductors leading to the flyer plate and the load coil. The magnetic pressure created by the opposing current accelerates the flyer plate to the target. The peak pressure striking the target is proportional to the flyer plate's velocity. The impulse is proportional to the flyer plate's momentum.

DATA SHEET 20.3. COLD X-RAY SIMULATOR: EXPLOSIVE LOADING SIMULATOR

Developing Critical Technology Parameter	Explosively driven flyer plates that simulate thermally generated pressures and impulses at the surface of generic-shaped space platforms of moderate size (e.g., RVs), with pressures < 1 kbar to 70 kbar (7 GPa) for fiber-reinforced organic ablators and up to 13 GPa for metal targets and impulses ranging from several hundred taps to > 7,000 taps (700 Pa-s).
Critical Materials	High explosives.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive

BACKGROUND

Explosive simulation techniques simulate combine shock and structural response to cold X-Rays. There are several different explosive simulation techniques, and each has its unique pros and cons:

- **SELT (Sheet-Explosive Loading Technique).** An explosive is placed in direct contact with the target surface and detonated. By selecting the properties of the explosive, a line-propagating detonation wave is produced. The velocity of the detonation wave is fast enough so that the shock wave produced in the target can be regarded as occurring uniformly over the target.
- **LIHE (Laser-Initiated High Explosive Technique).** This technique is similar to SELT inasmuch as the explosive is placed over the target surface. A two-layer explosive is used. A thin-layer, primary explosive is ignited first. This primary explosive triggers the main, secondary explosive. This technique produces a more uniform distribution of pressure over the target and can generate the lower impulse desired for simulation of cold X-Rays.
- **SPLAT (Spray Lead at Target Technique).** In this technique, strands of mild detonating fuze, with pentaerythritol tetranitrate (PETN) in its core, are suspended above the target. The explosion of PETN produces a spray of energetic particles that hit the target. The impact of this spray produces the desired impulse. This technique is limited to structural response investigations.

DATA SHEET 20.3. MIXING AND IGNITION

Developing Critical Technology Parameter	Techniques for improving mixing and ignition of oxidizers and fuels for reactions with surface emittance rates ≥ 150 cal/cm^2-sec at equivalent blackbody temperatures of 3,000 K or greater.
Critical Materials	Liquid oxygen; powdered aluminum; energetic materials that produce stabilized and spatially uniform reactions.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate to expensive.

BACKGROUND

Certain chemical reactions can reproduce some of the desired thermal radiation effects. The principal reason for using chemical reactions to reproduce thermal radiation effects is the low cost of operation. Chemical reactions have an inherent upper temperature limit that is well suited for thermal radiation simulation. The chemical reaction is most useful when the surface temperature of the reaction "flame" has an equivalent blackbody temperature greater than 3,000 K. Unfortunately, the mixing induced by the reaction process and other components needed to stabilize the reaction process also produces unwanted attenuating smokes or particle clouds. Also, the inability to start the reaction uniformly throughout the fuel mixture limits the intensity of the resulting radiation. Since more intensity and more fluence are always needed, developing new techniques for igniting the mixture and improving the mixing of the fuels is important.

DATA SHEET 20.3. THERMAL RADIATION TESTING

Developing Critical Technology Parameter	Thermal radiation test methodologies that define test conditions so that the target responds to the actual threat environment.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test devices that meet all the following criteria at 10 cm from the source to the target: provide at least a 50-percent total power transfer efficiency from energy supply (or stored energy if applicable) to the target at color temperatures equivalent to blackbody temperatures of 3,000 K, produce flux emittance levels larger than 150 cal/cm^2-sec over a minimum of 1-sec duration, and irradiate areas larger than 80 cm^2.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

The thermal energy deposited on surfaces by thermal radiation can melt surface layers, ignite the material, and produce thermal stresses that could cause component failures. Since direct simulation of the thermal radiation flux-time profile is difficult and is often limited to small areas, other less-expensive methods are needed to simulate possible failure modes. Simulating failure modes is accomplished by an appropriate combination of thermal radiation testing with lower-fidelity simulators, appropriately designed test conditions, and the proper interpretation of the test data. This testing methodology is evolving continuously because of new military equipment configurations, new materials, and new threat definitions.

DATA SHEET 20.3. THERMAL RADIATION INSTRUMENTATION

Developing Critical Technology Parameter	Test equipment and related instrumentation for determining the response of systems, components, and materials (SCM) for flux levels > 150 cal/cm^2-sec.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Characterizing the thermal radiation from these simulators requires specialized instrumentation that can provide accurate measurements for the full duration of the simulated conditions. The intense radiation environment can easily melt all known materials. In general, remote measurements are not feasible because the interaction of the thermal radiation with the test object typically produces smoke and intense light scattering that render remote methods useless. Improved direct measurement techniques, in the form of stresses and temperatures, are needed for characterizing the thermal radiation intensity and the response of the irradiated target.

DATA SHEET 20.3. THERMAL SPECTRAL MEASUREMENTS

Developing Critical Technology Parameter	Thermal spectral measurement devices that have a spectral resolution < 0.25 nm and a sampling rate faster than 80 ms.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

An important characteristic of the thermal radiation is the color content of the light. The color of a target's material affects how much of the total pulse is absorbed. Materials with dark colors tend to absorb more than materials with light colors. Simulators do not necessarily emulate the color spectrum of a nuclear pulse, but the ability to measure the color spectrum is important so that appropriate simulator exposure adjustments can be made. The intensity of the pulse and its short duration impose special design characteristics on measurement equipment. The spectral resolution of 0.25 nm and sampling rate of 80 ms for the full spectrum are needed to differentiate minimally the effects of color on a target's response to thermal radiation.

DATA SHEET 20.3. PLASMA DISCHARGE

Developing Critical Technology Parameter	Systems that provide for spatial uniformity or surface plasma discharges and cooling of electrodes with arc diameters and arc lengths > 1.0 cm and 10 cm, respectively, for currents > 1,000 A and input power > 300 kW.
Critical Materials	Materials that can sustain large current densities for sustained periods.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Plasma discharge is one of the most promising methods of generating a thermal radiation environment by non-nuclear means. Both arc and surface discharge technologies have been developed. The capability of these technologies is derived from the design of the electrodes, which must withstand intense currents. Ensuring that these electrodes remain operable for the duration of the radiation pulse is a challenge when high current densities are required. The listed system criteria would provide flux and fluence levels, radiated areas, and intensity uniformity of interest to nuclear burst thermal radiation response testing. Commercial applications for these current densities are nonexistent.

DATA SHEET 20.3. THERMAL ENVIRONMENT SIMULATION

Developing Critical Technology Parameter	Solar, electrical heaters, thermochemical, or other devices designed or specially designed to simulate the thermal environment in conjunction with the airblast resulting from the detonation of a nuclear weapon for peak fluxes > 100 cal/cm^2-sec and/or fluences ≥ 350 cal/cm^2 and having a test area ≥ 100 cm^2.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

High-flux, high-fluence thermal environments with a short, fast-rising pulse shapes are unique to nuclear weapons. The airblast from a nuclear explosion usually arrives during the more lengthy thermal pulse, with the relative timing of the two pulses highly dependent on the weapon yield, distance from the burst, and other conditions of the burst environment. The mere use of a combined thermal-blast environment is applicable only to nuclear weapon hardening evaluations, and the ability to control the parameters and relative timing of the two environments independently is a further strong indicator of its intended use.

DATA SHEET 20.3. THERMAL RADIATION MODELING

Developing Critical Technology Parameter	Theoretical models of nuclear detonations that describe the dimensional and radiant characteristics of the fireball as a function of the characteristics of the nuclear source, mode of burst, and atmospheric conditions.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software (codes and algorithms) validated against nuclear detonations or simulations of nuclear detonations for modeling the dimensional and radiant characteristics of the fireball as a function of the characteristics of the nuclear source, mode of burst, and atmospheric conditions.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

The thermal radiation pulse from a nuclear burst is very short and intense. It also has a unique time-dependent wavelength spectrum. Designing military systems that can survive nuclear-thermal-radiation-induced environments requires analytical tools that describe the conditions produced by these environments. Computer codes that mimic the thermal radiation produced by a nuclear burst have been developed. These codes have been compared with experimental measurement data from the U.S. aboveground nuclear test program of the 1950s and 1960s, and the parameters in these computer codes have been adjusted to match these measurements.

DATA SHEET 20.3. DETONATION OCCURRENCE

Developing Critical Technology Parameter	Prediction of the thermal signature of a nuclear detonation as a function of weapon yield, HOB, and other geometric parameters for a remote sensor.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software (codes and algorithms) validated against nuclear detonations or simulations of nuclear detonations for confirming the occurrence of a nuclear detonation and for estimating its yield and HOB.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

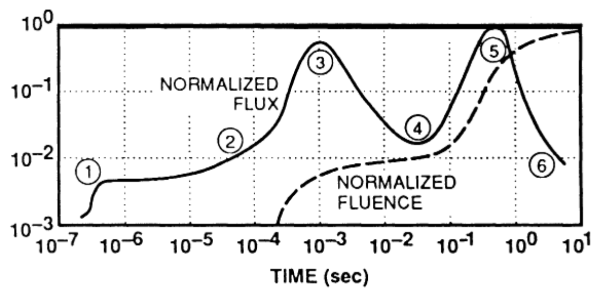
Computer codes that mimic the thermal radiation produced by a nuclear burst have been developed. These computer codes have been compared with experimental measurement data from the U.S. aboveground nuclear test program of the 1950s and 1960s, and the parameters in these codes have been adjusted to match these measurements. From current measurements by instruments in the field, certain types of codes are used to derive the exact characteristics of these previous bursts, including the weapon yield, HOB, and the location of the burst. Such data are used to distinguish between enemy and friendly fire and to assess the status of the battlefield.

DATA SHEET 20.3. WAVEFORM CONTROL

Developing Critical Technology Parameter	Control the waveform-generating capability of the simulation device.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software (codes and algorithms) validated against nuclear detonations or simulations of nuclear detonations that control the waveform-generating capability of the simulation device.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

As shown in Figure 20.3-7, the thermal pulse is actually quite complex. It consists of six distinct features. Developing the simulation tools necessary to describe these features adequately remains a technical challenge.



1. **X-ray Veil:** At detonation, the heated warhead produces radiation, primarily X-rays, that creates a sphere (or veil) of plasma that absorbs the radiation from within.
2. **Shock Formation Begins:** The outer edge of this veil is cool and is very opaque to soft interior X-rays. This trapped interior energy radiates to the surrounding cool air, enlarging the fireball. As bomb vapors expand to the edge of the fireball, these vapors form a strong, expanding hydrodynamic shock. The front of this shock becomes sharper and hotter and radiates more strongly.
3. **Shock Formation is Complete—First Maximum:** As the outrunning shock sharpens, its surface radiates like a blackbody at the shock temperature and radius. The shock expands, increasing the radiating surface, which then cools.
4. **Minimum:** As the shock front temperature drops below 6,000 K, a thermal radiation minimum begins to form as the opaque shock front becomes transparent to radiation from the interior.
5. **Second Maximum:** When the fireball becomes so transparent that radiation from the innermost, hottest regions are visible, the second thermal peak occurs. By the second peak, the fireball has radiated only about one-quarter of its total energy.
6. **Late-Time Radiative Phase:** Subsequently, as the fireball cools, the thermal radiation decreases.

Figure 20.3-7. Time Sequence of Thermal Pulse From a Nuclear Detonation Below 100,000 Feet (Source: Reference 1)

CITED REFERENCE

1. "Thermal Radiation From Nuclear Weapons," Brochure published by the Defense Nuclear Agency, February 1991.

SECTION 20.4—IONIZING RADIATION

Highlights

- Ionizing radiation can damage or destroy microelectronic integrated circuits (ICs) by several mechanisms.
- Although high doses and dose rates are more predictably effective in damaging microcircuits, single event effects (SEEs) are becoming increasingly common and devastating as individual device size decreases.
- Transient radiation effects on electronics (TREE) and system-generated electromagnetic pulse (SGEMP) are primarily problems for exoatmospheric systems.
- It is difficult to predict theoretically the system survivability of microelectronic systems.
- Many foreign countries have the capability to produce rad-hard microelectronics.
- Source region electromagnetic pulse (SREMP) is generated by the electric currents produced by ionizing radiation from nuclear bursts below 20 km in altitude and can be effective within a radius of 3 to 8 km from the burst point, depending on weapon yield.
- SREMP adversely affects communication facilities and power grids and may be effective against systems in blast-hardened targets, such as missile launchers.
- Simulating SREMP is difficult because the electromagnetic and ionizing radiation environments must be produced simultaneously.
- Pulsed-power technologies are critical to the simulation of TREE, SGEMP, and SREMP.
- Many TREE, SGEMP, and SREMP pulsed-power technologies are relevant for particle accelerators, particle beam weapons, and laser weapons.
- Pulsed-power techniques for TREE, SGEMP, and SREMP are expensive.

OVERVIEW

The technologies in this section address the ionizing effects of nuclear radiation produced by a nuclear detonation and methods for simulating these effects in laboratory-scale facilities. The technologies include TREE, SGEMP, SREMP, and pulsed power (for simulation).

TREE and SGEMP are discussed together as TREE/SGEMP. They are primarily concerned with space-based military systems. These effects are caused by the same nuclear detonation (i.e., they occur concurrently). They are caused by the interaction between the nuclear-weapon-generated, high-energy charged particles, gamma rays, and X-rays and the system. In addition, they occur within the physical boundary of the system being affected.

A good example of TREE/SGEMP effects is the transient ionization that occurs within a satellite that is being attacked by a high-altitude nuclear detonation. TREE effects pertain to damage or upset caused by the direct interaction of the ionizing radiation with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). SGEMP effects are attributed to internal electromagnetic fields and electric currents produced by the ionizing radiation. These electric fields and currents could be caused, for example, by secondary electron emission produced when gamma rays hit an interior surface.

Specific TREE/SGEMP technologies include methods for predicting these effects on a component basis, for evaluating these effects on a system, for developing methods for hardening components against them, and for simulating them.

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

Specific SREMP technologies include methods for predicting its ionizing and electromagnetic environment, methods for simulating its effect in the laboratory, and methods for hardening systems against its effect.

Simulating TREE/SGEMP and SREMP requires the generation of copious amounts of high-energy charged particles, X-rays, gamma rays, and neutrons. A special simulator is required for each type of radiation. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation). This feat is accomplished using pulsed-power electrical systems. The pulsed-power technologies addressed in this section discuss methods of generating the required radiation levels—total dose and dose rates for the various types of ionizing radiation.

A large number of specific technologies are necessary to provide the pulsed power necessary to simulate the full spectrum of nuclear radiation. For example, the Z-pinch is a unique source for low-energy (cold) X-rays. The Blumlein or coaxial cable forms part of the pulse-forming network. Large banks of high-quality, low-loss capacitors, and fast opening and closing switches (with low resistance in the closed state) provide the required energy storage and switching. Marx generators and Van de Graaf generators provide high-current voltage generation.

LIST OF TECHNOLOGY DATA SHEETS
20.4. IONIZING RADIATION

DATA SHEET 20.4. TREE/SGEMP SIMULATORS

Developing Critical Technology Parameter	Pulsed gamma-ray, X-ray, electron beam, and ion beam sources that simulate a nuclear weapons radiation environment with dose rates > 10^{11} rad(Si)/sec over a volume that is large enough to test military components, subsystems, and systems; diagnostic and test equipment that can operate in dose rates > 10^{11} rad(Si)/sec.
Critical Materials	Optical fibers and semiconductor materials that can operate in dose rates that are > 10^{11} rad(Si)/sec.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Substantiated multidimensional shock-wave computer programs that incorporate constitutive models of composite materials, blow-off, fracture, nucleation, growth of flaws, buckling, brittle fracture, and delamination and that can operate and evaluate the performance of components, subsystems, and systems in a nuclear-weapon-generated environments > 10^{11} rad(Si)/sec.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

TREE and SGEMP are primarily concerned with space-based military systems. These effects are caused by the same nuclear detonation (i.e., they occur concurrently). They are caused by the interaction between the nuclear-weapon-generated high-energy charged particles, gamma rays, and X-rays and the system. In addition, they occur within the physical boundary of the system being affected.

A good example of TREE/SGEMP effects is the transient ionization that occurs within a satellite that is being attacked by a high-altitude nuclear detonation. TREE effects pertain to damage or upset caused by the direct interaction of the ionizing radiation with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). SGEMP effects are attributed to internal electromagnetic fields and electric currents produced by the ionizing radiation. These electric fields and currents could be caused, for example, by secondary electron emission produced when gamma rays hit an interior surface.

Simulating TREE/SGEMP and SREMP requires the generation of copious amounts of high-energy charged particles, X-rays, gamma rays, and neutrons. A special simulator is required for each type of radiation. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation). This feat is accomplished using pulsed-power electrical systems.

Figure 20.4-1 is an example of the type and size of simulator required to evaluate the response of systems to TREE and SGEMP. The AURORA simulator, no longer in use, was capable of generating 8.5 MeV electrons at a beam current of 200 kA and a pulse width of 100 ns. Also of interest is the enormous physical size of the simulator in comparison to the size of human being, the test object, and the irradiation area (less than 1 m^2). Although current and future simulators may have greater capability than AURORA, they will be of comparable size.

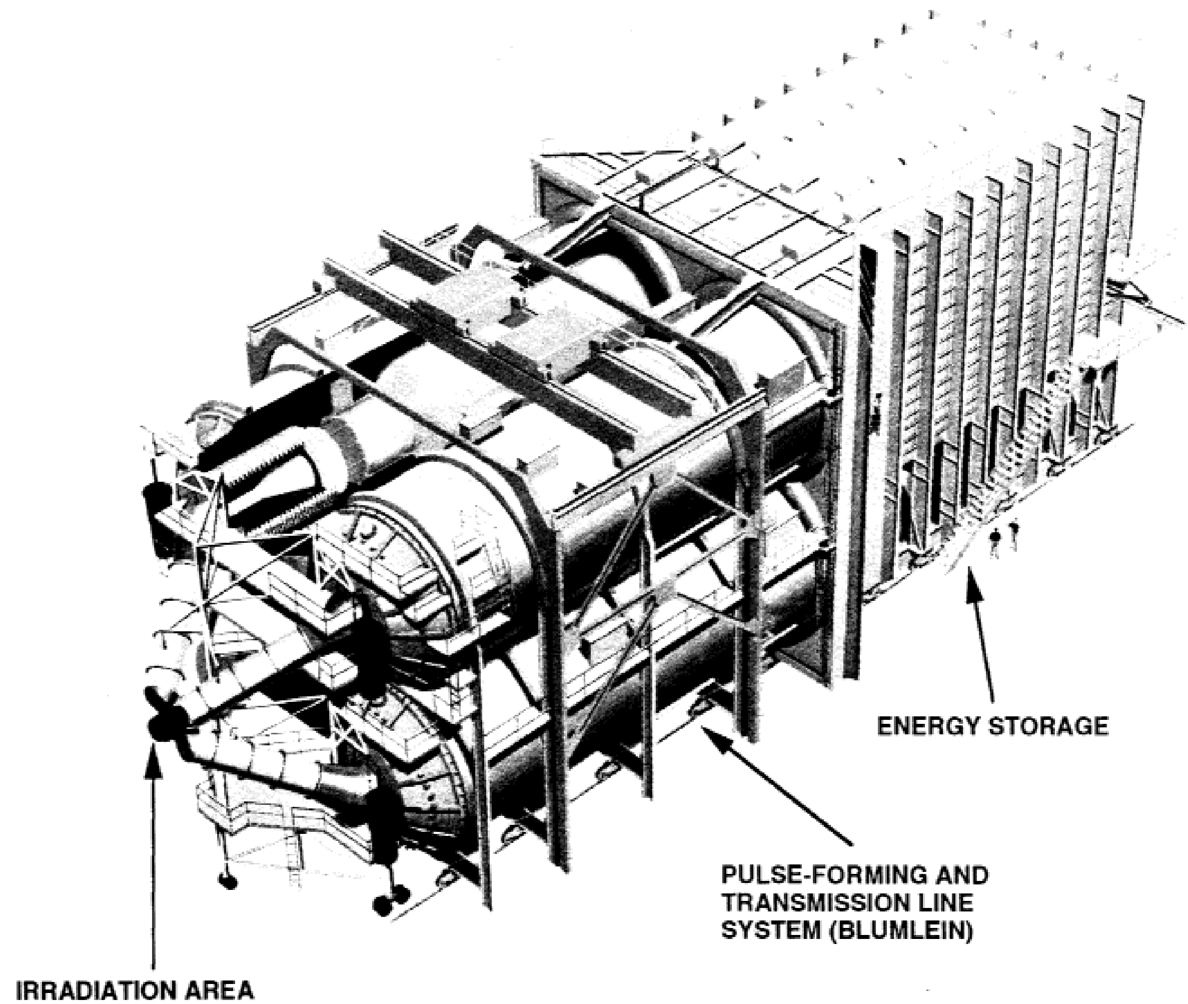


Figure 20.4-1. Sketch of AURORA Simulator (Source: Reference 1)

CITED REFERENCE

1. Defense Nuclear Agency Radiation Facilities brochure.

DATA SHEET 20.4. TREE/SGEMP HARDENING

Developing Critical Technology Parameter	Systems, subsystems, and components that are hardened against nuclear-weapon-generated environments that exceed 10^{11} rad(Si)/sec.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test systems that can evaluate the performance of components, subsystems, and systems required to operate in a radiation environment $> 10^{11}$ rad(Si)/sec.
Unique Software	Substantiated radiation computer codes and algorithms that can perform TREE/ SGEMP hardening assessments and tradeoff studies at either the component, sub-system, or system level and can evaluate "operate-through capability."
Major Commercial Applications	None identified.
Affordability	Expensive to very expensive.

BACKGROUND

TREE and SGEMP are primarily concerned with space-based military systems. These effects are caused by the same nuclear detonation (i.e., they occur concurrently). They are caused by the interaction between the nuclear-weapon-generated high-energy charged particles, gamma rays, and X-rays and the system. In addition, they occur within the physical boundary of the system being affected.

A good example of TREE/SGEMP effects is the transient ionization that occurs within a satellite that is being attacked by a high-altitude nuclear detonation. TREE effects pertain to damage or upset caused by the direct interaction of the ionizing radiation with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). SGEMP effects are attributed to internal electromagnetic fields and electric currents produced by the ionizing radiation. These electric fields and currents could be caused, for example, by secondary electron emission produced when gamma rays hit an interior surface.

TREE and SGEMP hardening is concerned with hardware and software methods that mitigate or eliminate the effects of nuclear-radiation-generated transient ionization. These methods include circumvention techniques and the development of special techniques for rad-hard microelectronics.

DATA SHEET 20.4. SREMP SIMULATORS

Developing Critical Technology Parameter	Systems that can generate simultaneously a radiation environment that exceeds 10^9 rad(Si)/sec, and an electromagnetic environment for a nuclear weapon detonation ≤ 5 km in altitude; pulsers that simulate local exterior effects and distant exterior regions.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Current generators that produce an action > 2 x 10^7 A^2-sec, currents that exceed 20 kA, or rates of current change > 2 x 10^{10} A/sec; current generators that simulate SREMP-induced long-line currents at high voltages with the following combined characteristics: load current > 2 x 10^4 A, load voltage > 100 kV, full width at half maximum (FWHM) ≥ 30 μs.
Unique Software	Substantiated computer codes and related algorithms that can predict the SREMP waveform and the coupling of this waveform to military systems.
Major Commercial Applications	None identified.
Affordability	Expensive to very expensive.

BACKGROUND

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

Simulating the SREMP ionization and electromagnetic environment in the source region (also called the interior environment) requires the generation of copious amounts of high-energy charged particles, X-rays, gamma rays, and neutrons in the lower atmosphere and the concurrent generation of the electromagnetic field caused by the motion of these charged particles. As we move away from the immediate vicinity of the detonation, the ionization level drops, and we need only then to be concerned about the electromagnetic environment. In this latter region, the only type of simulators required are those that can generate the electromagnetic waveform.

DATA SHEET 20.4. COLD X-RAY EFFECTS SIMULATION

Developing Critical Technology Parameter	X-rays under 15 keV produced by Z-pinches or other devices that can be used to approximate the cold X-ray spectrum produced by a high-altitude nuclear detonation; sources > 40 kJ using 1- to 10-keV X-rays and > 5 kJ using 5- to 20-keV X-rays in under 100 ns over an area > 1 cm^2; debris mitigation techniques; X-ray optic components with reflectivity > 20 percent; methods for collecting and focusing X-rays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

Cold X-rays, defined as those that have energies under 15 keV, are especially damaging to space systems. The coupling of the weapon debris to the atmosphere in a high-altitude detonation creates these cold X-rays, which are absorbed on the surface of the space platforms and can generate shock waves in the systems. These shock waves can cause structural damage: TMS, TSR, and other malfunctions to optical sensor systems.

Copious amounts of cold X-rays can be simulated by using a plasma radiation source such as a Z-pinch, an ion source, or, in some cases, an FXR source. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation).

DATA SHEET 20.4. BREMSSTRAHLUNG SOURCES

Developing Critical Technology Parameter	X-rays produced by electrons with energies > 100 keV hitting a high-Z target and can approximate either the gamma rays or hot X-rays generated by a nuclear detonation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

Hot X-rays, defined as those having energies greater than 100 keV, are produced by a nuclear detonation. Because these X-rays are so energetic, a significant fraction of hot X-rays travel through the skin of a satellite and can strike electrical components such as semiconductors, insulators, and microelectronic ICs. Transient ionization is produced, which then leads to unwanted currents and voltages in the system. Hot X-rays cause TREE and SGEMP effects that can lead to temporary or permanent damage.

Bremsstrahlung sources produce hot X-rays. Some bremsstrahlung sources can also produce photons with energies in the MeV range. In this case, these sources simulate gamma rays. Figure 20.4-2 shows hot X-rays that are produced by an FXR machine.

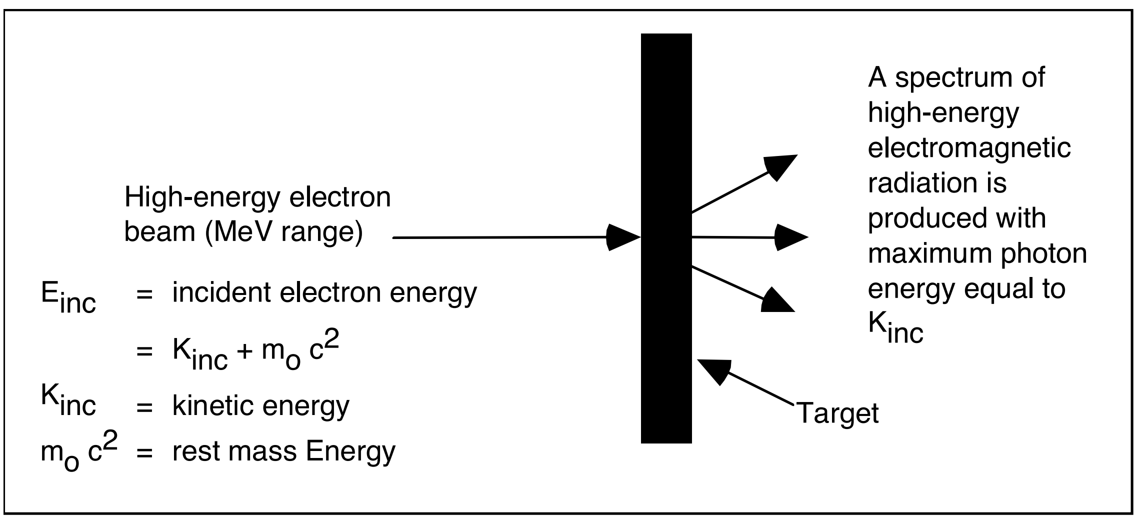


Figure 20.4-2. The FXR Principle

DATA SHEET 20.4. NEUTRON BEAM SOURCES

Developing Critical Technology Parameter	Neutron beam sources capable of generating > 10^{13} neutrons/cm^2 that approximate the spectrum generated by either a fission or fusion device.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

High-energy neutrons are produced by a nuclear detonation. Because they are so energetic, a significant fraction of high-energy neutrons travel through the skin of a satellite and can strike electrical components such as semiconductors, insulators, and microelectronic ICs. Transient ionization is produced, which then leads to unwanted currents and voltages in the system. High-energy neutrons cause TREE that may lead to temporary and/or permanent damage. Neutron beam sources at the flux levels required to simulate the neutron spectrum from a nuclear detonation are obtained from fission or fusion devices.

The three basic sources for simulating high-energy neutrons produced in a nuclear detonation are pulsed nuclear reactors, photoneutrons produced in the sequence shown in Figure 20.4-3, and the relatively new process called spallation. The spallation process creates high-energy neutrons by striking a nucleus with 800-MeV protons. This creates an excited nucleus, which relaxes to a less excited state by releasing a low-energy neutron.

Figure 20.4-3. Sequential Process for Generating Photoneutrons

DATA SHEET 20.4. ION BEAM SOURCES

Developing Critical Technology Parameter	Ion beam sources that can be used to approximate the cold X-ray deposition in materials generated by a nuclear detonation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

Cold X-rays, defined as those that have energies under 15 keV, are especially damaging to space systems. The coupling of the weapon debris to the atmosphere in a high-altitude detonation creates these cold X-rays, which are absorbed on the surface of the space platforms and can generate shock waves in the systems. These shock waves can cause structural damage: TMS, TSR, and other malfunctions to optical sensor systems.

Copious amounts of cold X-rays can be simulated by using ion beam sources that can generate cold X-rays in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation). This is of particular interest for assessing the vulnerability of space platforms to a nuclear detonation.

Figure 20.4-4 is a simplified drawing of the pinch-reflex diode (PRD) ion source. As summarized by the developers, the operating principle is as follows:

> Electrons that are drawn off the thin ring cathode and accelerated across the gap are constrained to reflex through the thin plastic anode foil by magnetic forces behind the foil and electric forces in the diode gap. Electron reflexing produces the anode plasma (from which beam protons are extracted) by surface flashover and collisional heating.

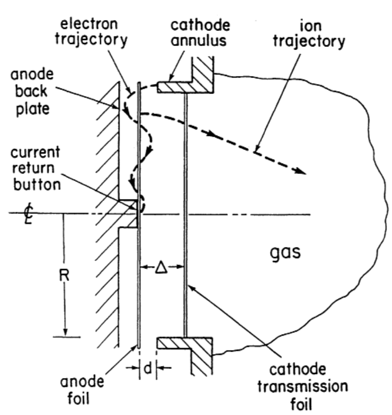


Figure 20.4-4. Simplified Drawing of the Pinch-Reflex Ion Diode (Source: Reference 1)

CITED REFERENCE

1. D. Mosher, S. Stephanakis, and F. Young, “Light Ion Beams for Material-Response Simulation,” Presented at the Advanced Pulsed-Power Conference, 31 July–3 August 1990, BDM International, Inc., Albuquerque, NM.

DATA SHEET 20.4. VACUUM POWER FLOW

Developing Critical Technology Parameter	Systems for transporting, coupling, or converging electrical power in vacuum pulse lines at impedances < 0.1 ohm and power levels > 2.5 TW to an area < 500 cm^2. When used in connection with a Z-pinch, the vacuum power flow system should be capable for delivering > 10 MA rising in < 30 ns.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

Pulsed-power generating and conditioning systems and their associated loads (e.g., vacuum diodes that convert the pulsed system's electrical output to a photon or particle beam) are valuable tools for evaluating the hardness and survivability of critical military systems. Of particular importance are nuclear weapons effects (NEW) simulators that can produce pulses with peak power greater than 25 TW from sources that have impedance less than 0.1 ohm and have vacuum power flow and conditioning that can couple to a radiating load having a circular area less than 500 cm^2. The particle energies involved range from the upper energy limit of the UV band (0.124 keV) to the MeV and tens of MeVs associated with the gamma ray and neutrons emitted from a nucleus.

Vacuum power flow transports the charged particles to the diode. These energetic charged particles interact with the diode, producing X-rays.

DATA SHEET 20.4. DOSE-RATE UPSET

Developing Critical Technology Parameter	Procedures that are unique to testing device dose-rate upset and survivability that simulates a nuclear weapon radiation environment of ≥ 10^{11} rad(Si)/sec.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Gamma-ray, X-ray, and neutron sources that simulate the output from a nuclear detonation.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

This technology deals with evaluating the effects on components, circuits, subsystems, and systems of transient ionization produced by the high-energy gamma rays, high-energy X-rays, and neutrons produced by the detonation of a nuclear weapon and the protons and heavy ions from galactic and solar sources. These forms of radiation interact directly with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). Unwanted electrical transients caused by these interactions can cause signals to deviate from their normal state, ultimately leading to upset and possibly permanent damage. The higher the level of transient radiation, the greater the probability of system upset.

DATA SHEET 20.4. SENSOR DEGRADATION

Developing Critical Technology Parameter	Development of devices or circuit approaches that minimize sensor degradation from gamma debris. Any level that improves this capability is useful.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Signal-processing software to remove gamma-ray-induced noise.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

This technology deals with transient ionization effects on sensors produced by high-energy gamma rays from a nuclear detonation. Gamma rays interact directly with sensors, producing incorrect information from the sensor to other elements of the system. At sufficiently high levels of gamma radiation, permanent damage to the sensor can result. In either case, temporary upset or permanent damage to the sensor can cause the system to take a variety of incorrect actions.

DATA SHEET 20.4. RADIATION TESTING

Developing Critical Technology Parameter	Diagnostic and test equipment that can evaluate the response of systems to dose rates $\geq 10^{11}$ rad(Si)/sec.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate to expensive.

BACKGROUND

This technology deals with developing and using equipment that can test systems under the influence of the transient ionization effects of high-energy gamma rays, high-energy X-rays, and neutrons produced by the detonation of a nuclear weapon. These forms of radiation interact directly with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). Unwanted electrical transients caused by these interactions can cause signals to deviate from their normal state, ultimately leading to upset and possibly damage. The higher the level of transient radiation, the greater the probability of system upset.

DATA SHEET 20.4. RADIATION-HARDENED (RAD-HARD) INSTRUMENTATION

Developing Critical Technology Parameter	Instrumentation using rad-hard components such as amplifiers, fiber-optic data links, and sensors that can test systems in environments that simulate the output from a nuclear detonation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial satellites; nuclear reactors; accelerators; cyclotrons; synchrotrons; medical applications.
Affordability	Moderate to expensive.

BACKGROUND

This technology deals with developing and using equipment that can test systems under the influence of the transient ionization effects of high-energy gamma rays, high-energy X-rays, and neutrons produced by the detonation of a nuclear weapon. These forms of radiation interact directly with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). Unwanted electrical transients caused by these interactions can cause signals to deviate from their normal state, ultimately leading to upset and possibly damage. The higher the level of transient radiation, the greater the probability of system upset.

DATA SHEET 20.4. RADIATION-HARDENED (RAD-HARD) COMPONENTS

Developing Critical Technology Parameter	Rad-hard microelectronic and photonic components, such as ICs, amplifiers, fiber-optic data links, opto-electronic data links, and sensors and other discrete devices, that can operate in radiation environments.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial satellites; nuclear reactors; accelerators; cyclotrons; synchrotrons; medical applications; military satellites and missiles.
Affordability	Moderate for individual components.

BACKGROUND

This technology deals with developing and using equipment that can test systems under the influence of the transient ionization effects of high-energy gamma rays, high-energy X-rays, and neutrons produced by the detonation of a nuclear weapon. These forms of radiation interact directly with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). Unwanted electrical transients caused by these interactions can cause signals to deviate from their normal state, ultimately leading to upset and possibly damage. The higher the level of transient radiation, the greater the probability of system upset.

DATA SHEET 20.4. VULNERABILITY ASSESSMENT

Developing Critical Technology Parameter	Physical and mathematical models that combine radiation transport, energy/charge deposition, radiation effects, and TREE susceptibility data to assess military systems' components and circuit vulnerability and to evaluate hardening approaches. Meaningful levels of improvement are desired.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes that incorporate physical and mathematical models of radiation transport, energy/charge deposition, radiation effects, and TREE susceptibility data to assess military systems' components and circuit vulnerability and to evaluate hardening approaches. Of particular importance are those codes that have been validated against experimental data obtained from TREE and SGEMP simulators.
Major Commercial Applications	Medical (radiation transport); food processing; material processing; nuclear reactors; satellites; accelerators.
Affordability	Expensive.

BACKGROUND

TREE and SGEMP are primarily concerned with space-based military systems. These effects are caused by the same nuclear detonation (i.e., they occur concurrently). They are caused by the interaction between the nuclear-weapon-generated high-energy charged particles, gamma rays, and X-rays and the system. In addition, they occur within the physical boundary of the system being affected.

A good example of TREE/SGEMP effects is the transient ionization that occurs within a satellite that is being attacked by a high-altitude nuclear detonation. TREE effects pertain to damage or upset caused by the direct interaction of the ionizing radiation with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). SGEMP effects are attributed to internal electromagnetic fields and electric currents produced by the ionizing radiation. These electric fields and currents could be caused, for example, by secondary electron emission produced when gamma rays hit an interior surface.

Because these nuclear radiation effects occur concurrently, the effects they cause may interact with each other. Rendering a robust vulnerability assessment requires accurate physical and mathematical models that can handle simultaneously the combined effects of the different radiation processes.

DATA SHEET 20.4. OPERATE THROUGH

Developing Critical Technology Parameter	Codes and algorithms that provide the capability of military systems to “operate-through” radiation environments produced by nuclear detonations. Meaningful levels of improvement are desired.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software that integrates codes and algorithms that enable a system to “operate-through” radiation environments produced by nuclear detonations. Of particular interest are those software techniques that have been validated against UGTs or aboveground simulations of nuclear detonations.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

TREE and SGEMP are primarily concerned with space-based military systems. These effects are caused by the same nuclear detonation (i.e., they occur concurrently). They are caused by the interaction between the nuclear-weapon-generated high-energy charged particles, gamma rays, and X-rays and the system. In addition, they occur within the physical boundary of the system being affected.

A good example of TREE/SGEMP effects is the transient ionization that occurs within a satellite that is being attacked by a high-altitude nuclear detonation. TREE effects pertain to damage or upset caused by the direct interaction of the ionizing radiation with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). SGEMP effects are attributed to internal electromagnetic fields and electric currents produced by the ionizing radiation. These electric fields and currents could be caused, for example, by secondary electron emission produced when gamma rays hit an interior surface.

Because these nuclear radiation effects occur concurrently, the effects they cause may interact with each other. Developing software techniques that enable a military system to “operate-through” TREE and SGEMP increases its ability to complete its mission.

DATA SHEET 20.4. PREDICTION OF TREE/SGEMP

Developing Critical Technology Parameter	Physical and mathematical models that combine gamma-ray, X-ray, and neutron radiation transport, energy/charge deposition, radiation effects, and TREE susceptibility data to assess military systems' components and circuit vulnerability. Of particular interest are those models that have been experimentally validated. Meaningful levels of improvement over existing capabilities are desired.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Physical and mathematical models that combine gamma-ray, X-ray, and neutron radiation transport, energy/charge deposition, radiation effects, and TREE susceptibility data to assess military systems components and circuit vulnerability. Of particular interest are those models that have been validated from either nuclear tests and/or aboveground simulation that includes empirically derived parameters such as dose rate, risetime, and energy spectrum of the radiation components.
Major Commercial Applications	Medical (radiation transport); food processing; material processing; nuclear reactors; satellites; accelerators.
Affordability	Moderate to expensive.

BACKGROUND

This technology deals primarily with TREE and SGEMP effects on space-based military systems. These effects are caused by the same nuclear detonation (i.e., they occur concurrently). They are caused by the interaction between the nuclear-weapon-generated high-energy charged particles, gamma rays, and X-rays and the system. In addition, they occur within the physical boundary of the system being affected.

A good example of TREE/SGEMP effects is the transient ionization that occurs within a satellite that is being attacked by a high-altitude nuclear detonation. TREE effects pertain to damage or upset caused by the direct interaction of the ionizing radiation with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). SGEMP effects are attributed to internal electromagnetic fields and electric currents produced by the ionizing radiation. These electric fields and currents could be caused, for example, by secondary electron emission produced when gamma rays hit an interior surface.

Because these nuclear radiation effects occur concurrently, the effects they cause may interact with each other. A prediction tool that combines all the important features of the interactions is of great importance in modeling the combined TREE and SGEMP interaction with a system.

Rigorous prediction of TREE and SGEMP effects is extremely complicated, as evidenced by Figure 20.4-5 and Figure 20.4-6. Improving our understanding of the physical mechanisms shown in these figures is of great interest since it will lead to simplifying the calculations.

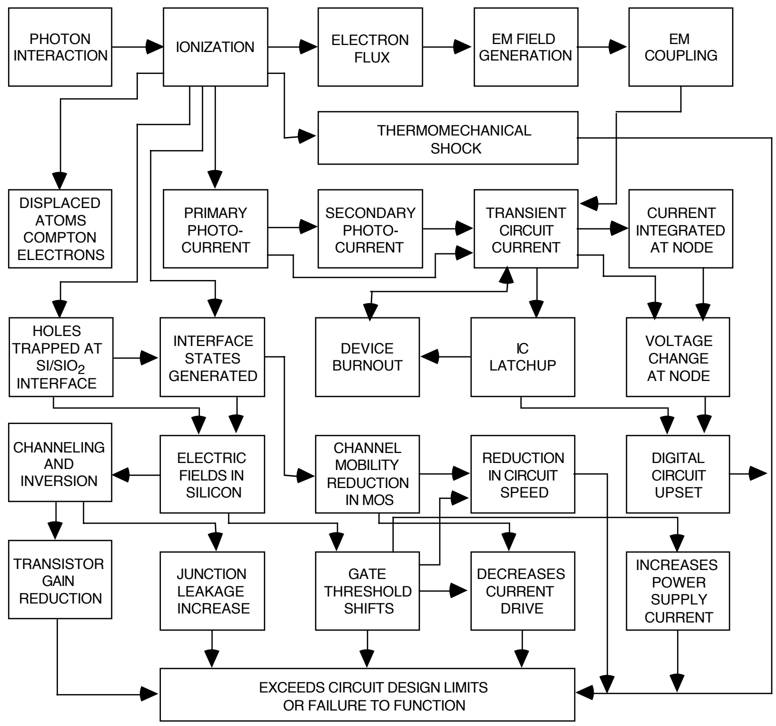


Figure 20.4-5. Flow Diagram for Ionization Effects in Electronics (Source: Reference 1)

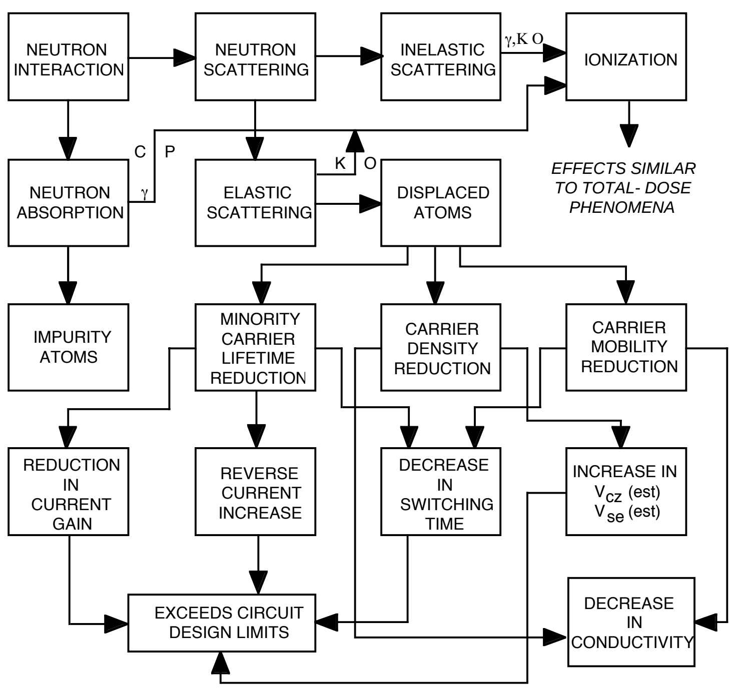


Figure 20.4-6. Flow Diagram for Displacement Effects in Electronics (Source: Reference 1)

CITED REFERENCE

1. J.E. Gover, *Basic Radiation Effects in Electronics Technology*, Sandia Corporation, Sandia Corporation Report, February 1984.

DATA SHEET 20.4. NUCLEAR HARDNESS SOFTWARE

Developing Critical Technology Parameter	Codes and algorithms for TREE and SGEMP hardening that use information from nuclear tests, nuclear weapons design, and/or aboveground simulations that include empirically derived parameters such as dose rate, risetime, and spectrum and allow a designer to evaluate tradeoffs in hardening vs. threat, weight, and cost. Meaningful levels of improvement are desired.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Developing software for codes and algorithms for predicting TREE and SGEMP hardness of systems. This software should include not only validate physical models, but also information from nuclear tests, nuclear weapons design, and/or aboveground simulations that include empirically derived parameters such as dose rate, risetime, and spectrum. The software should allow a designer to evaluate tradeoffs in hardening vs. threat, weight, and cost. Examples include signal-processing approaches that enhance operability of a sensor in persistent nuclear environments.
Major Commercial Applications	None identified.
Affordability	Moderate cost if implemented early in design of system. Can be very expensive if implemented later.

BACKGROUND

This technology deals primarily with TREE and SGEMP effects on space-based military systems. These effects are caused by the same nuclear detonation (i.e., they occur concurrently). They are caused by the interaction between the nuclear-weapon-generated high-energy charged particles, gamma rays, and X-rays and the system. In addition, they occur within the physical boundary of the system being affected.

A good example of TREE/SGEMP effects is the transient ionization that occurs within a satellite that is being attacked by a high-altitude nuclear detonation. TREE effects pertain to damage or upset caused by the direct interaction of the ionizing radiation with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). SGEMP effects are attributed to internal electromagnetic fields and electric currents produced by the ionizing radiation. These electric fields and currents could be caused, for example, by secondary electron emission produced when gamma rays hit an interior surface.

Because these nuclear radiation effects occur concurrently, the effects they cause may interact with each other. Software-hardening approaches that account for all the important features of the interactions is of great importance in modeling the combined TREE and SGEMP interaction with a system.

DATA SHEET 20.4. NUCLEAR HARDNESS HARDWARE

Developing Critical Technology Parameter	Specific subassembly circuits or components specially designed to implement nuclear hardness and surveillance techniques such as current limiting, power strobing, nuclear event detection, current compensation, cryogenic total ionizing dose radiation hardening, minimization of sensor degradation because of debris gamma, matching radiation-induced voltage threshold shifts, special packaging to reduce circuit or component susceptibility to nuclear-weapon-induced X-ray effects, and so forth. Meaningful levels of improvement over existing capabilities are desired.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate cost if implemented early in design of system. Can be very expensive if implemented later.

BACKGROUND

This technology deals primarily with TREE and SGEMP effects on space-based military systems. These effects are caused by the same nuclear detonation (i.e., they occur concurrently). They are caused by the interaction between the nuclear-weapon-generated high-energy charged particles, gamma rays, and X-rays and the system. In addition, they occur within the physical boundary of the system being affected.

A good example of TREE/SGEMP effects is the transient ionization that occurs within a satellite that is being attacked by a high-altitude nuclear detonation. TREE effects pertain to damage or upset caused by the direct interaction of the ionizing radiation with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). SGEMP effects are attributed to internal electromagnetic fields and electric currents produced by the ionizing radiation. These electric fields and currents could be caused, for example, by secondary electron emission produced when gamma rays hit an interior surface.

Because these nuclear radiation effects occur concurrently, the effects they cause may interact with each other. Hardware-hardening approaches that account for all the important features of the interactions is of great importance in modeling the combined TREE and SGEMP interaction with a system.

DATA SHEET 20.4. NUCLEAR HARDNESS SURVEILLANCE

Developing Critical Technology Parameter	Cost-effective and easy-to-implement methods for verifying the integrity of specific subassembly circuits or components specially designed to implement nuclear hardness. Examples include surveillance techniques such as current limiting, power strobing, nuclear event detection, current compensation, cryogenic total ionizing dose radiation hardening, minimizing sensor degradation because of debris gamma, matching radiation-induced voltage threshold shifts, and special packaging to reduce circuit or component susceptibility to nuclear-weapon-induced X-ray effects. Meaningful levels of improvement over existing capabilities are desired.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software that supports built-in-test-equipment (BITE) to minimize the cost of implementing a nuclear hardness surveillance program.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

This technology deals primarily with TREE and SGEMP effects on space-based military systems. These effects are caused by the same nuclear detonation (i.e., they occur concurrently). They are caused by the interaction between the nuclear-weapon-generated high-energy charged particles, gamma rays, and X-rays and the system. In addition, they occur within the physical boundary of the system being affected.

A good example of TREE/SGEMP effects is the transient ionization that occurs within a satellite that is being attacked by a high-altitude nuclear detonation. TREE effects pertain to damage or upset caused by the direct interaction of the ionizing radiation with electrical components (e.g., semiconductors, insulators, and microelectronic ICs). SGEMP effects are attributed to internal electromagnetic fields and electric currents produced by the ionizing radiation. These electric fields and currents could be caused, for example, by secondary electron emission produced when gamma rays hit an interior surface.

Because these nuclear radiation effects occur concurrently, the effects they cause may interact with each other. Software-hardening approaches that account for all the important features of the interactions is of great importance in modeling the combined TREE and SGEMP interaction with a system.

DATA SHEET 20.4. ELECTROMAGNETIC PROBES AND SENSORS

Developing Critical Technology Parameter	Sensors of probes designed to measure electric or magnetic fields, current (including Compton current), voltage, or air conductivity in radiation environments that are $> 10^{10}$ rad(Si)/sec.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

Unlike the simulation technology for high-altitude electromagnetic pulse (HEMP), which has been developed to a highly sophisticated level over several decades, SREMP simulation is still in the formative stage. The difficulty is the requirement for simultaneous exposure of a system to ionizing and nonionizing radiation.

DATA SHEET 20.4. SREMP CURRENT GENERATORS

Developing Critical Technology Parameter	Current generators that produce an action > 2×10^8 A^2/sec and currents that exceed 200 kA or rates of rise that exceed 2×10^{11} A/sec.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate to expensive.

BACKGROUND

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

SREMP current generators simulate driving the current into systems. Injecting these currents into systems is useful for determining the susceptibility of systems to the SREMP environment.

DATA SHEET 20.4. SREMP ENVIRONMENTS

Developing Critical Technology Parameter	Mathematical and physical models that describe the following processes: neutron inelastic scattering and capture; sources from Monte Carlo codes, when these sources or derived SREMP calculation that have been compared with nuclear test data, radiation-induced conductivity of air, and bulk materials for dose rates that are $> 10^{12}$ rad(Si)/sec; electrical properties of fireballs formed by the interaction of X-rays and debris from nuclear bursts with the air and the interaction of these fireballs with electrical conductors; the behavior of SREMP-produced electrical discharges in soil for currents > 50 kA and durations longer than 100 μs; and the development and use of techniques for interpreting SREMP system effects response data from SREMP simulator testing.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes and algorithms that address the models that describe the following processes: neutron inelastic scattering and capture; the dynamics of radiation-induced conductivity of air; the generation of low-altitude fireballs; the electrical properties of fireballs formed by the interaction of X-rays and debris from nuclear bursts with the air; the interaction of these SREMP fireballs with electrical conductors; and the response of systems to the SREMP environment. Of particular interest are those computer codes that have been validated against UGT data or aboveground SREMP simulations.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

As we move away from the immediate vicinity of the detonation, the ionization level drops, and we only have to be concerned about the electromagnetic environment. In this latter region, the only type of simulators required are those that can generate the electromagnetic waveform.

DATA SHEET 20.4. SREMP COUPLING

Developing Critical Technology Parameter	Mathematical and physical models that predict the coupling of the SREMP environment to exposed electrical conductors in a system. Of particular interest are those models that have been compared with SREMP simulations.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Validated computer codes and algorithms that predict the coupling of the SREMP environment to exposed electrical conductors in a system.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

SREMP coupling to systems is more difficult than the traditional electromagnetic coupling problems of electromagnetic compatibility (EMC) because we have to account for charge accretion on insulators caused by the ionized background and for the time-dependent conductivity.

DATA SHEET 20.4. ELECTRIC SURGE ARRESTERS (ESAs)

Developing Critical Technology Parameter	ESAs for use online operating at 480 V or less and capable of handling charge transfers of 5 kilocoulombs or more (significantly greater than those used for lighting) in a time of < 0.1 sec.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Inexpensive.

BACKGROUND

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

DATA SHEET 20.4. FAST DISCONNECTS

Developing Critical Technology Parameter	Rapidly disconnect elements of systems when unwanted large currents (in the 100-kA range) pass through an electrical connection. Times of interest range from a few milliseconds to 100 ms. A fast disconnect can either be a single device or a system and can be active or passive. The speed of disconnect is also a factor and is system-application dependent.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Inexpensive.

BACKGROUND

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

DATA SHEET 20.4. POWER-ISOLATION DEVICES

Developing Critical Technology Parameter	Ability to interrupt electrical power to selected systems during unwanted surges. This stops or limits the development of unwanted fast transients. Currents of interest are in the 100-kA range. Times of interest range from a few milliseconds to 100 ms.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

DATA SHEET 20.4. RESISTIVE ISOLATION CABLES

Developing Critical Technology Parameter	Ability to interrupt power surges in relatively low-power systems by introducing resistive losses. This is similar to the action of a fuze. Possible applications include communication lines.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Inexpensive.

BACKGROUND

SREMP is produced by a low-altitude nuclear detonation. The SREMP environment is unique and often includes ionizing radiation and electromagnetic fields acting together on the same component.

As a general rule, the target is assumed to be far enough away from the nuclear detonation so that it is not dominated by the ionizing radiation. Instead, the ambient air surrounding the target is ionized by the gamma rays. Strong electric currents are produced in the atmosphere in the region of the burst. These strong electrical currents and related electromagnetic fields couple to electrical and electronic systems, for example, by a power cable coming out of a building. This cable can also be affected concurrently by the ambient ionizing radiation.

DATA SHEET 20.4. INSULATORS

Developing Critical Technology Parameter	Insulators that are capable of operating at electric field stresses exceeding 100 kV/cm.
Critical Materials	Materials that will sustain electrical field stresses exceeding 100 kV/cm for pulse lengths less than a microsecond.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Electrical power industry.
Affordability	Highly variable.

BACKGROUND

The ability to achieve the desired pulse risetime and repeatability of performance depends, in large measure, on the integrity of the switches leading from the Marx to the Blumlein and from the Blumlein to the power conditioning/load unit. Four categories of closing switches can be used in pulsed power:

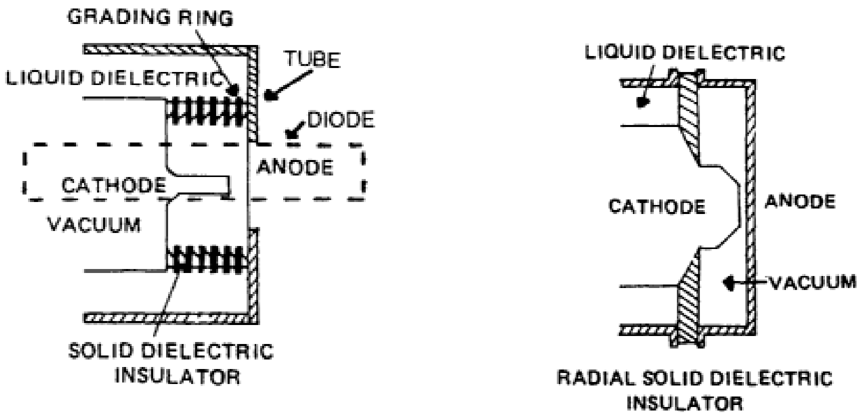
1. Gas switches
2. Liquid switches
3. Vacuum gaps
4. Solid dielectric switches.

For NWE simulation (NWES), the two principal types of closing switches (spark gaps) are gas and liquid. The performance of these switches depends on their breakdown strengths and inductance and the resistance of the channel during breakdown. The two most common liquids are oil and water.

The key technologies in the Marx generator–Blumlein system are:

- Voltage breakdown
- The quantification of the inductive and resistive properties of the switches under pulsed conditions.

These voltage breakdown and switching considerations also apply to the more commonly used transmission lines. In more recent simulators, regular transmission lines have been preferred over Blumleins because they can supply more current instead of higher voltage. Beyond a certain point, voltage is sufficient. Providing more current increases power. Figure 20.4-7 shows two examples of insulation methods used to create a vacuum diode.



(a) Graded insulator ring stack **(b) Low-inductance radial insulator**

Figure 20.4-7. Vacuum Diode Insulators (Source: Reference 1)

CITED REFERENCE

1. A.D. Blumlein, *J.I.E.E.,* Vol. 93, Part IIIA, 1946, p. 1098.

DATA SHEET 20.4. BREMSSTRAHLUNG DIODE

Developing Critical Technology Parameter	A diode, when coupled to $\leq$ 25 TW electrical power is capable of delivering any of the following bremsstrahlung radiation levels at an end-point energy of < 2.0 MeV: combined capability > 20 krad(Si) over 500 cm^2 and > 2×10^{12} rad(Si)/sec over 500 cm^2.
Critical Materials	Materials that efficiently convert high-energy electrons into high-energy photons.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Hot X-rays, defined as those having energies greater than 100 keV, and gamma rays are produced by a nuclear detonation. Because they are so energetic, a significant fraction of hot X-rays and gamma rays travel through the skin of a satellite and can strike electrical components such as semiconductors, insulators, and microelectronic ICs. Transient ionization is produced, which then leads to unwanted currents and voltages in the system. Hot X-rays and gamma rays cause TREE and SGEMP effects that can lead to temporary and/or permanent damage. Simulation of these effects is necessary to improve the survivability of military systems in a nuclear engagement.

DATA SHEET 20.4. MULTIPLE SERIES DIODE

Developing Critical Technology Parameter	Assembly of multiple series electron diodes and components capable of operation at power levels ≥ 6.0 TW.
Critical Materials	Materials that efficiently convert high-energy electrons into high-energy photons.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Hot X-rays, defined as those having energies greater than 100 keV, and gamma rays are produced by a nuclear detonation. Because they are so energetic, a significant fraction of hot X-rays and gamma rays travel through the skin of a satellite and can strike electrical components such as semiconductors, insulators, and microelectronic ICs. Transient ionization is produced, which then leads to unwanted currents and voltages in the system. Hot X-rays and gamma rays cause TREE and SGEMP effects that can lead to temporary and/or permanent damage. Simulation of these effects is necessary to improve the survivability of military systems in a nuclear engagement.

In comparison to a single diode, a multiple series diode allows a higher voltage, higher impedance accelerator (easier to build) to produce the high-fidelity radiation source of a low-voltage/low-impedance accelerator (hard to build). Figure 20.4-8 is a cross-sectional schematic of a triple series diode.

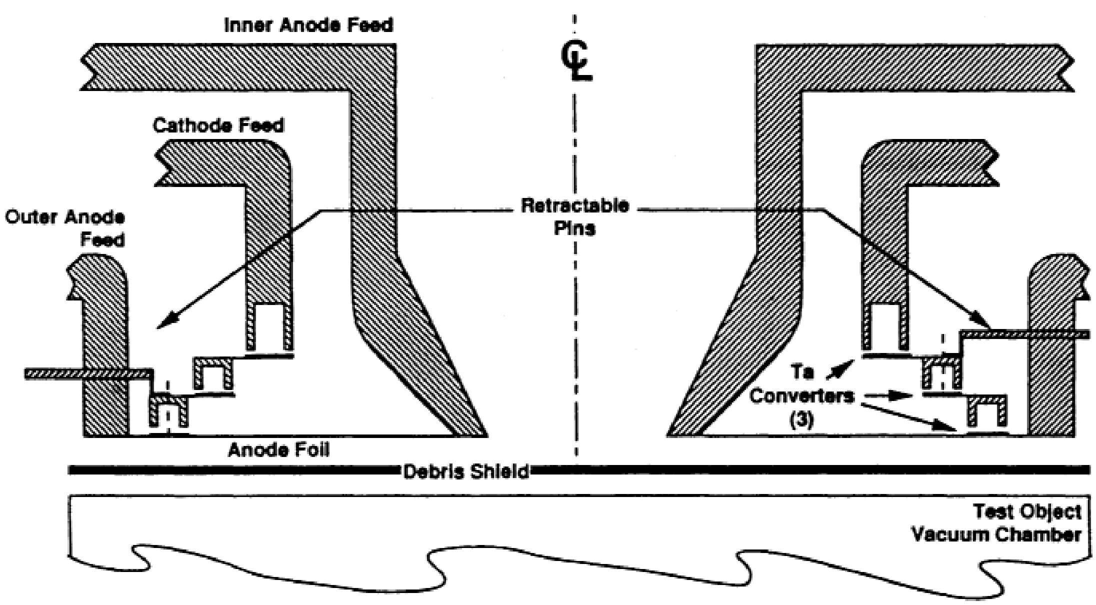


Figure 20.4-8. A Sectional Schematic of the DOUBLE EAGLE Triple Series Diode Configuration (Source: Reference 1)

CITED REFERENCE

1. J.S. Meachum and J.C. Riordan, "Triple Series Diode Improves Bremsstrahlung Source Efficiency and Simulation Fidelity," Presented at the Advanced Pulsed-Power Conference, 31 July–3 August 1990, BDM International, Inc., Albuquerque, NM.

DATA SHEET 20.4. SOURCE-DIODE COUPLING

Developing Critical Technology Parameter	Any diode that, when coupled to any electrical power source, is capable of delivering any of the following bremsstrahlung radiation levels at an end-point energy of $\leq$ 1.8 MeV: • Combined capability > 20 krad(Si) over 10,000 cm^2 and > 5 × 10^{11} rad(Si)/sec over 10,000 cm^2 • Combined capability > 80 krad(Si) over 1,000 cm^2 and > 2 × 10^{12} rad(Si)/sec over 1,000 cm^2.
Critical Materials	Materials that efficiently convert high-energy electrons into high-energy photons.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Hot X-rays, defined as those having energies greater than 100 keV, and gamma rays are produced by a nuclear detonation. Because they are so energetic, a significant fraction of hot X-rays and gamma rays travel through the skin of a satellite and can strike electrical components such as semiconductors, insulators, and microelectronic ICs. Transient ionization is produced, which then leads to unwanted currents and voltages in the system. Hot X-rays and gamma rays cause TREE and SGEMP effects that can lead to temporary and/or permanent damage. Simulation of these effects is necessary to improve the survivability of military systems in a nuclear engagement.

DATA SHEET 20.4. COLD X-RAY DEBRIS SHIELD

Developing Critical Technology Parameter	Debris shields with > 90-percent transmission for photons ≤ 15 keV from Z-pinch source while maintaining a vacuum seal over areas > 100 cm^2 at dose levels that are > 100 krad(Si).
Critical Materials	Materials that improve the transmission of cold X-rays and can restrain the debris. Examples include beryllium and kapton foils.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Cold X-rays, defined as those that have energies under 15 keV, are especially damaging to space systems. The coupling of the weapon debris to the atmosphere in a high-altitude detonation creates these cold X-rays, which are absorbed on the surface of the space platforms and can generate shock waves in the systems. These shock waves can cause structural damage: TMS, TSR, and other malfunctions to optical sensor systems.

Copious amounts of cold X-rays can be simulated by using a plasma radiation source such as a Z-pinch, an ion source, or, in some cases, an FXR source. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation).

Ensuring that only the cold X-rays of interest strike the test object (sample) is important. However, debris substances other than the cold X-rays might reach the sample. These substances may include material from the pre-shot ambient environment, pieces of metal, plasma-related matter, and so forth. Also of concern are the undesirable sub-keV photons, which can adversely impact the survivability of the debris shield. Minimizing this debris, while allowing for the passage of the desired keV to hit the sample, is accomplished by using a debris shield.

Two generic types of debris shields are those that survive permanently after the shot and those that do not survive. The fundamental issue is to minimize the debris that strikes the window. This is accomplished in a series of steps. Initially, the sources of debris in the Z-Pinch are reduced as much as possible by selecting appropriate materials. The UV filter is used to reduce dramatically the sub-keV photons generated in the Z-Pinch. The baffles help mitigate the debris. The window must allow desirable photons to pass through, absorb the remaining lower-energy photons (i.e., those not removed by the UV filter), and retain its structural integrity during the process so that it can be used again. Thus, the design of an appropriate transmission window for photon energies above 1 keV is a critical technology. If the debris shield does not have to survive, higher sample exposures are sometimes possible. For example, inserting a beryllium window that can delay the debris by tens of microsecond permits the sample to be tested against cold X-rays.

DATA SHEET 20.4. WARM X-RAY DEBRIS SHIELD

Developing Critical Technology Parameter	Debris shields with > 90-percent transmission for photons with energy between 15 and 60 keV from a bremsstrahlung spectrum with endpoint energy < 0.5 MeV, while maintaining a vacuum seal over areas > 100 cm^2 at dose levels > 100 krad(Si). This is a warm X-ray source.
Critical Materials	Materials that improve the transmission of warm X-rays and can restrain the debris. Examples include polyethylene and metal restraining fixtures.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Warm X-rays, defined as those that have energies under 15 keV, are damaging to space systems. The coupling of the weapon debris to the atmosphere in a high-altitude detonation creates these warm X-rays. A fraction of the warm X-rays are absorbed on the surface of the space platforms, causing shock waves. The remaining fraction of the warm X-rays propagate through the surface and interact with interior structural membranes, causing differential heating. The net result of warm X-rays is the development of TMS, TSR, and other malfunctions to optical sensor systems.

Simulating copious amounts of warm X-rays can be accomplished using a plasma radiation source such as a Z-pinch, an ion source, or, in some cases, an FXR source. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation).

Ensuring that only the warm X-rays of interest strike the test object (sample) is important. However, debris substances other than the warm X-rays might reach the sample. These substances may include material from the pre-shot ambient environment, pieces of metal, plasma-related matter, and so forth. Also of concern are the undesirable sub-keV photons, which can adversely impact the survivability of the debris shield. Minimizing this debris, while allowing for the passage of the desired keV to hit the sample, is accomplished by using a debris shield.

DATA SHEET 20.4. HOT X-RAY DEBRIS SHIELD

Developing Critical Technology Parameter	Debris shields with > 90-percent transmission for photons with energy > 60 keV from a bremsstrahlung spectrum with endpoint energy > 0.5 MeV, while maintaining a vacuum seal over areas > 100 cm^2 at dose levels > 100 krad(Si).
Critical Materials	Materials that improve the transmission of hot X-rays and can restrain the debris. Examples include kelvar and aluminum.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Hot X-rays, defined as those that have energies greater than 60 keV, cause TREE and SGEMP effects in space systems and are especially damaging to space systems. These X-rays travel through the skin of the space platform and strike interior electronics. Simulation of hot X-rays can be accomplished using an FXR system. The high-energy electrons that strike the diode produce debris and the desired hot X-rays but also produce unwanted debris. To evaluate the hot X-ray effects on the target and exclude the unwanted debris effects, using a debris shield is necessary. This shield allows the hot X-rays to interact with the target while minimizing the unwanted debris.

DATA SHEET 20.4. FAST CLOSING VALVES

Developing Critical Technology Parameter	Fast closing valves that close an aperture > 1 cm^2 in < 5 μs and limit debris to < 100 particles/mm^2. This technology is an improvement to the debris shield system.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Cold X-rays, defined as those that have energies under 15 keV, are especially damaging to space systems. The coupling of the weapon debris to the atmosphere in a high-altitude detonation creates these cold X-rays, which are absorbed on the surface of the space platforms and can generate shock waves in the systems. These shock waves can cause structural damage: TMS, TSR, and other malfunctions to optical sensor systems.

Copious amounts of cold X-rays can be simulated by using a plasma radiation source such as a Z-pinch, an ion source, or, in some cases, an FXR source. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation).

Ensuring that only the cold X-rays of interest strike the test object (sample) is important. However, debris substances other than the cold X-rays might reach the sample. These substances may include material from the pre-shot ambient environment, pieces of metal, plasma-related matter, and so forth. Using a debris shield is one way of eliminating this debris, while allowing for the passage of the desired keV to hit the sample.

An enhancement to the debris shield is an Ultra-Fast Closing Valve (UFCV). The essential idea of the UFCV is to stop the debris after the cold X-rays have passed the point of the valve action. The is made possible by constructing a long path and using the fact that the velocity of the debris (~ 10^4 m/sec) is slow compared with other relevant time scales.

DATA SHEET 20.4. X-RAY FOCUSING

Developing Critical Technology Parameter	X-ray optic components capable of collecting and focusing to > 5 cal/cm^2 over an area > 0.1 cm^2 for X-ray energies > 1 keV. X-ray optic components with reflectivity > 20 percent at incident angles > 10 degrees for energies > 1 keV that are operable at exposure levels > 1 cal/cm^2.
Critical Materials	Materials that can support the propagation of X-rays at small-angle scattering, with low loss upon reflection. X-ray optic components with reflectivity > 20 percent.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Cold X-rays, defined as those that have energies under 15 keV, are especially damaging to space systems. The coupling of the weapon debris to the atmosphere in a high-altitude detonation creates these cold X-rays, which are absorbed on the surface of the space platforms and can generate shock waves in the systems. These shock waves can cause structural damage: TMS, TSR, and other malfunctions to optical sensor systems.

Copious amounts of cold X-rays can be simulated by using a plasma radiation source such as a Z-pinch, an ion source, or, in some cases, an FXR source. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation).

The Z-Pinch is an isotropic radiation source, an important factor in simulation. In this case, the solid angle subtended by the target determines the amount of energy that actually hits a test object. The incident X-ray fluence on a test object can be increased by focusing a portion of the isotropic radiation from the Z-Pinch. The basic technology is similar to that used in fiber optics. Fibers and related X-ray optic components that can support the propagation of X-rays at small-angle scattering, with low loss upon reflection, are required.

DATA SHEET 20.4. DEBRIS MITIGATION

Developing Critical Technology Parameter	Any debris mitigation technique that protects test articles from debris to levels < 100 particles/mm^2, with < 5 μm diameter particles, when tested to X-ray fluences > 1 cal/cm^2 at energies > 2 keV and pulses < 100 ns over an area > 1.0 cm^2.
Critical Materials	Materials that improve the transmission of cold X-rays and can restrain the debris.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Cold X-rays, defined as those that have energies under 15 keV, are especially damaging to space systems. The coupling of the weapon debris to the atmosphere in a high-altitude detonation creates these cold X-rays, which are absorbed on the surface of the space platforms and can generate shock waves in the systems. These shock waves can cause structural damage: TMS, TSR, and other malfunctions to optical sensor systems.

Copious amounts of cold X-rays can be simulated by using a plasma radiation source such as a Z-pinch, an ion source, or, in some cases, an FXR source. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation).

Ensuring that only the cold X-rays of interest strike the test object (sample) is important. However, debris substances other than the cold X-rays might reach the sample. These substances may include material from the pre-shot ambient environment, pieces of metal, plasma-related matter, and so forth. Debris mitigation techniques include methods and materials that allow sufficient amounts of cold X-rays to hit the sample while minimizing the amount of debris that hits the sample. Debris shields and fast closing valves are methods that are currently available.

DATA SHEET 20.4. COLD X-RAY SOURCES

Developing Critical Technology Parameter	Cold X-ray sources capable of producing > 400 kJ using 1–3 keV X-rays with pulse widths < 30 ns over an area > 1 cm^2 and > 5 kJ using 5–15 keV X-rays with pulse widths < 30 ns over an area > 1 cm^2.
Critical Materials	Materials that can be brought to high temperatures and radiate large amounts of energy in the cold X-ray region.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software that predicts the behavior of high-temperature plasmas and includes theoretical models that describe high-energy radiation hydrodynamic processes that include turbulence. When turbulence is included, the model should be capable of computing the plasma's resistivity, viscosity, and heat conductivity transport coefficients.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

Cold X-rays, defined as those that have energies under 15 keV, are especially damaging to space systems. The coupling of the weapon debris to the atmosphere in a high-altitude detonation creates these cold X-rays, which are absorbed on the surface of the space platforms and can generate shock waves in the systems. These shock waves can cause structural damage: TMS, TSR, and other malfunctions to optical sensor systems.

Copious amounts of cold X-rays can be simulated by using a plasma radiation source such as a Z-pinch, an ion source, or, in some cases, an FXR source. In each case, the radiation must be generated in less than the tens-of-nanosecond time regime (i.e., characteristic of the release from a nuclear detonation).

DATA SHEET 20.4. ELECTRON DIODE SOURCES

Developing Critical Technology Parameter	Electron-beam diode sources and related beam propagation hardware capable of producing electron beams with < 3-percent variation in fluence over 5 cm distance for current densities > 30 kA/cm^2 averaged over 25 cm^2 at electron-beam endpoint energies < 2 MeV in < 50 ns. This technology covers electron-beam systems that produce the required uniformity and proper time scale of dose over useful areas in excess of published capabilities.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Relativistic electron transport codes.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

X-rays are especially damaging to space systems. Depending on their energy, they can cause a variety of adverse effects. Hot X-rays cause TREE and SGEMP; warm X-rays contribute in part to TMS and TSR; and cold X-rays are the principal cause of TMS. An important element for predicting the response of a system to the X-ray radiation from a nuclear detonation is simulating the energy deposition of X-rays. The technology addressed here is concerned with using electron beams to determine this energy deposition.

DATA SHEET 20.4. ION SOURCES

Developing Critical Technology Parameter	Ion beam sources and related beam propagation hardware capable of producing ion beam fluences > 25 cal/cm^2 in < 50 ns over area > 1,000 cm^2 with variations in fluences < 5 percent over 5 cm^2 or < 10 percent over 1,000 cm^2. This technology covers ion beam systems that produce the required uniformity and proper time scale of dose over useful areas in excess of published capabilities.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Ion beam transport codes.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

X-rays are especially damaging to space systems. Depending on their energy, they can cause a variety of adverse effects. Hot X-rays cause TREE and SGEMP; warm X-rays contribute in part to TMS and TSR; and cold X-rays are the principal cause of TMS. An important element for predicting the response of a system to the X-ray radiation from a nuclear detonation is simulating the energy deposition of X-rays. The technology addressed here is concerned with accomplishing this using ion beams.

DATA SHEET 20.4. NEUTRON SOURCES

Developing Critical Technology Parameter	Neutron sources capable of producing neutron bursts with > 10^{14} neutrons/cm^2 over an area > 1,000 cm^2 in < 1 ms. Neutron doses of this level require subcritical nuclear assemblies.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

TREE effects, which are caused by a nuclear detonation, are primarily concerned with military systems. They are caused by the interaction of nuclear-weapon-generated, high-energy charged particles, gamma rays, and X-rays with the system. In addition, they occur within the physical boundary of the system being affected. A good example of TREE effects is the displacement damage on electrical components (e.g., semiconductors, insulators, and microelectronic ICs) caused by neutrons. In addition, neutrons produce some ionization in the microelectronics, along with the ionization caused by the gamma rays that are produced along with the neutrons.

Neutron effects on microelectronic components differ in systems, depending on whether they are space borne or terrestrial. In the exoatmospheric environment, the neutrons that strike a space platform have a more energetic energy spectrum than those that interact in the terrestrial environment. At high altitudes, neutrons travel with little attenuation or scattering from the nuclear detonation to the target. At the lower altitudes, they interact with the air, losing energy in the process but also producing gamma rays. Thus, targets at lower altitudes will experience a broader but lower-neutron-energy spectrum and an enhanced gamma-ray spectrum than those at higher altitudes.

This technology is concerned with total dose neutron effects on systems.

SECTION 20.5—ELECTROMAGNETIC EFFECTS

Highlights

- HEMP is generated by electric currents in the atmosphere. These currents are produced by Compton scattering of the gamma radiation from a high-altitude nuclear detonation.
- The electromagnetic waves from HEMP can degrade the performance of ground and airborne systems that are more than 1,500 km from the burst.
- Methods used to harden systems against HEMP are essentially the same as those used in the areas of EMC and electromagnetic interference (EMI). These methods are available in the open literature.
- The atmospheric ionization produced by a high-altitude nuclear detonation can interrupt trans-satellite and satellite-to-ground communications.
- Adverse operational effects on communications caused by high-altitude nuclear detonations include lowering of the SNR, fading, and the resultant reduced information rate for communication channels.
- Simulation of atmospheric ionization effects on communication equipment can be accomplished using hardware-in-the-loop (HITL) methods.

OVERVIEW

This section covers electromagnetic effects caused by the generation of HEMP and the propagation of electromagnetic waves in a nuclear-disturbed atmosphere. These two topics are connected because both are caused—albeit in different ways—by the ionization produced by a nuclear detonation in the atmosphere.

HEMP is produced by a nuclear detonation that occurs between 20 and 40 km above the earth's surface. Gamma rays from the detonation produce a burst of energetic electrons, and these energetic electrons create the electromagnetic pulse. This pulse is of short duration (the total duration being on the order of microseconds). However, the electromagnetic pulse created by HEMP is capable of propagating over 1,000 miles and adversely affecting unhardened electronic systems. The interaction of the pulse with a system is purely electromagnetic, similar to other forms of EMI.

Specific HEMP technologies discussed include the generation of HEMP as a function of weapon yield and HOB, coupling of HEMP electromagnetic fields to electronic systems, simulation of HEMP, methods for mitigating the effects of HEMP interaction, and maintaining the hardness of electronic systems against harmful electromagnetic pulses over a system's lifetime.

When electromagnetic waves transmitted by communication, radar, navigation, and other electronic systems transverse an ionized region of the atmosphere, these waves suffer attenuation, distortion, and refraction. These effects result in information that is impaired or totally disrupted. Nuclear detonations that occur at altitudes 30 km or more above the earth's surface produce enhanced levels of ionization that persist long enough to be of interest to military operations. The electromagnetic propagation technologies address the generation of the enhanced ionization and assess the effect of the ionization on propagation. Of particular interest are propagation considerations for trans-satellite and satellite-to-ground communications caused by modifications to the propagation media. Operational effects include lowering of the SNR, fading, and reduced information rate for communication channels. The ability to simulate these effects using actual HITL is very important.

Specific technologies in this area include those that deal with the adverse effects of unwanted electromagnetic fields on systems and the electromagnetic effects that interfere with the propagation of electromagnetic waves.

BACKGROUND

HEMP

A nuclear explosion is accompanied by the immediate release of gamma rays produced by the nuclear reactions within the warhead. When this explosion occurs above the atmosphere, as shown in Figure 20.5-1, these gamma rays produce high-energy free electrons when they eject the electrons from the atoms in the atmosphere. This process is called Compton scattering, and it is effective in the altitude range between 20 and 40 km. The earth's magnetic field lines then trap these moving electrons, resulting in an asymmetric-oscillating electric current that gives rise to a transient radiated electromagnetic field. This transient radiated electromagnetic field is called HEMP.

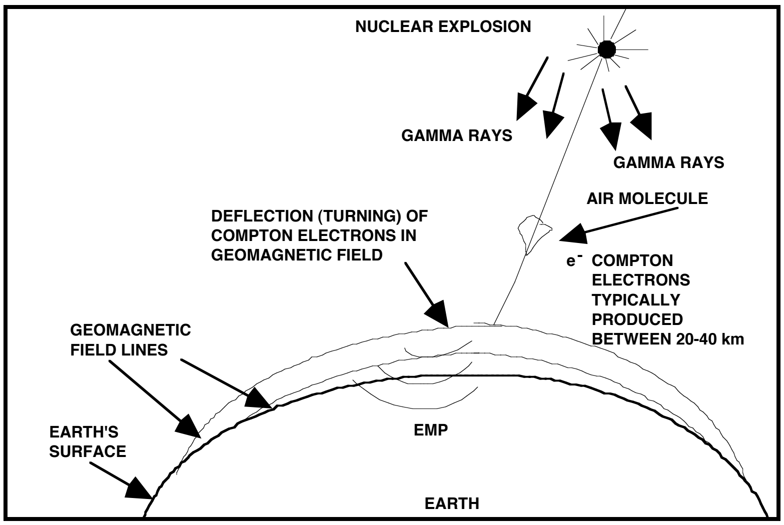


Figure 20.5-1. Generation of HEMP (Source: Reference 1)

Figure 20.5-1 shows the path of a single electron generated by a single gamma ray. Because these gamma rays produce Compton electrons over a large spatial region between 20 and 40 km above the earth, a robust electromagnetic source radiates coherently. This electromagnetic radiation radiates toward the earth and can reach large segments of the earth's surface. On the earth's surface, this radiation can affect hosts of terrestrial, airborne, army, and navy systems, as shown in Figure 20.5-2.

The time duration of the HEMP generated by these Compton electrons typically extends up to 1 μs. An important feature of HEMP is the extensive range and wide area over which it can affect a large number of military systems. Large-peak HEMP fields can exist at moderate heights above the earth's surface out to ground ranges determined by the tangent radius, R_t, from the detonation to the earth's surface (see Figure 20.5-3). For a spherical earth,

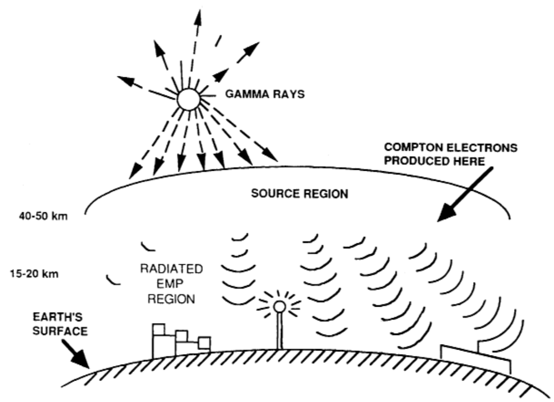
$$R_t = R_e \cos^{-1}\left(\frac{R_e}{R_e + HOB}\right) \quad , \tag{1}$$

where R_e is the earth's radius of 6,371 km.[3]

In addition to the "early-time" HEMP, scattered gamma-ray photons and inelastic gamma rays from weapon neutrons produce an "intermediate-time" signal extending from about 1 μs to 1.0 sec. Also, the motion of the geomagnetic field, caused by energetic debris and enhanced ionization and heating of the E-region of the ionosphere, produces a "late-time" magnetohydrodynamic-electromagnetic pulse (MHD-EMP).

---

3 We can appreciate the importance of HEMP as a threat if we imagine a hypothetical high-altitude nuclear weapon burst occurring over the middle of the continental United States (CONUS). For example, a 300-km HOB detonation occurring in Kansas can adversely affect military systems anywhere in CONUS.



HEMP CAN EXPOSE ALL SYSTEMS WITHIN LOS

- **Wide Area Coverage**
- **High Field Strengths (50 kV/m)**
- **Broad Frequency Band (DC to greater than 100 MHz)**
- **Absence of Most Other Nuclear Weapons Effects**

Figure 20.5-2. Main Features of HEMP (Source: Reference 2)

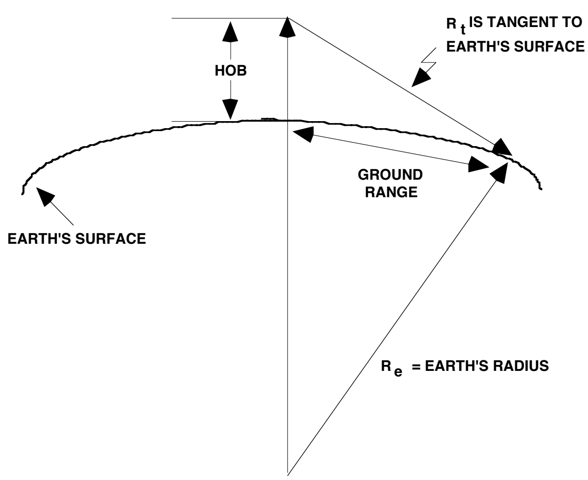


Figure 20.5-3. Determination of Ground Range

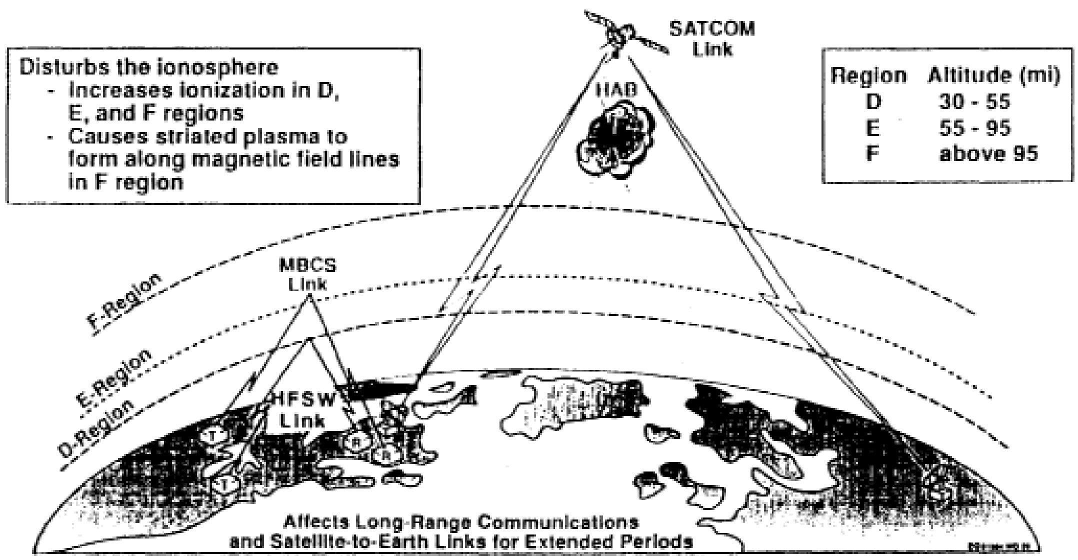
Note for Figure 20.5-3: *Drawing is not to scale.*

Each of the three HEMP components ("early-time," "intermediate-time," and "late-time") affects electronic systems differently because the waveforms of the electromagnetic field are different. HEMP usually has the most important effect on a system and, therefore, has received the most attention.

Propagation

Nuclear detonations in the atmosphere can adversely affect the performance of communication and navigation systems, radar, and passive and active sensor systems. The degree to which these systems are affected depends on factors such as HOB, weapon yield, time of day, cloud cover, latitude and longitude, electromagnetic wave propagation path, and time following the detonation. For communications systems and radar, the unwanted effects of nuclear detonations are attributed to the increased electron density and structure that the detonation creates in the atmosphere. The most important problems for IR, visible, and UV sensor systems are the IR, visible, and UV radiation emanating from the heated regions. Laser communication systems also may be susceptible to the background IR radiation of a fireball or heated region when in the receiver's field of view (FOV).

Figure 20.5-4 is an overview of nuclear effects on military communication systems resulting from a nuclear high-altitude burst (HAB) that occurs above the F-region of the ionosphere. Table 20.5-1 provides a summary of these effects, which extend from very low frequency (VLF) to extremely high frequency (EHF), and includes a characterization of its level measured in decibels (dB) and its duration.



Blackout:	A large attenuation of the transmitted signal that causes the received SNR to fall below unity.
Scintillation:	A signal-fading/waveform distortion effect caused by multipath propagation through the structured plasma. The structured plasma is produced by the interaction of HAB-induced ionized regions with the earth's magnetic field.

Figure 20.5-4. Overview of Nuclear Effects From a High-Altitude Detonation on Communication Systems (Source: Reference 3)

Table 20.5-1. Summary of High-Altitude Nuclear Effects on Military Communication Systems From VLF to EHF (Source: Reference 3)

Band	Mode	Type of Effect	Level of Effect	Duration
VLF 3 kHz–30 kHz	SW	Absorption Phase changes	15 dB $> \pm 2\partial$	30 min 5 min
LF 30 kHz–300 kHz	SW	Absorption Phase changes	30 dB $\sim \pm 2\partial$	1 hr 5 min
MF 300 kHz–3 MHz	SW	Absorption	50 dB	4 hr
HF 3 MHz–30 MHz	SW	Absorption	100 dB	8 hr
VHF 30 MHz–300 MHz	MBCS	Absorption Noise	60 dB 10 dB	2 hr days

Table 20.5-1. Summary of High-Altitude Nuclear Effects on Military Communication Systems From VLF to EHF (Source: Reference 3) (Continued)

Band	Mode	Type of Effect	Level of Effect	Duration
UHF 300 MHz–3 GHz	TROPOSAT	Noise Absorption Scintillation	6 dB 10 dB 30 dB	30 min 10 min 4 hr
SHF 3 GHz–30 GHz	SAT	Absorption Scintillation	3 dB 10 dB	5 min 2 hr
EHF 30 GHz–300 GHz	SAT	Scintillation	6 dB	30 min

From Table 20.5-1, extensive degradation in the medium-frequency sky wave (MFSW), high-frequency sky wave (HFSW), and very high frequency (VHF) [Meteor Burst Communications System (MBCS)] systems results from the absorption of these radio waves in the D- and E-regions of the ionosphere. A condition known as "black-out" occurs when the absorption becomes so high that useful communication is degraded. In the ultrahigh frequency (UHF), super high frequency (SHF), and EHF bands, significant disruption effects occur—not so much from absorption, but from a phenomenon known as "scintillation." In this case, the signal waveform is severely distorted by fading and multipath, which may or may not be accompanied by attenuation.

CITED REFERENCES

1. P. Dittmer et al., *DNA EMP Course Study Guide,* Defense Nuclear Agency, DNA Report DNA-H-86-68-V2, May 1986.

2. Maj. D. Richlin, "Nuclear Weapons Effects on Aircraft," Presented at the Aircraft Combat Survival Course, Naval Post Graduate School, Monterey, CA, April 1993.

3. *DNA EMP Engineering Handbook for Ground-Based Facilities, Volume II – Design and Engineering,* Booz-Allen and Hamilton, Inc., DNA-H-86-60-V2, November 1986.

LIST OF TECHNOLOGY DATA SHEETS
20.5. ELECTROMAGNETIC EFFECTS

DATA SHEET 20.5. SYSTEM-LEVEL HEMP SIMULATOR

Developing Critical Technology Parameter	Generate peak electric fields exceeding 5 kV/m, risetime < 10 ns, and pulse duration < 1 μs over volumes large enough to test complete military systems.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Pulsers capable of delivering rates of voltage rise > 100 kV/ns into < 100 ohms or rates of current rise > 1 kA/ns into impedances > 100 ohms into a port on a system.
Unique Software	Substantiated computer programs and related algorithms for computing the on-test-target electric field generated by the pulser.
Major Commercial Applications	Testing electronic and communication systems against wide range of unwanted electromagnetic signals.
Affordability	Moderate.

BACKGROUND

HEMP is produced by a nuclear detonation that occurs between 20 and 40 km above the earth's surface. Gamma rays from the detonation produce a burst of energetic electrons, and these energetic electrons create the electromagnetic pulse. This pulse is of short duration (the total duration being on the order of microseconds). However, the electromagnetic pulse created by HEMP is capable of propagating over 1,000 miles and adversely affecting unhardened electronic systems. The interaction of the pulse with a system is purely electromagnetic, similar to other forms of EMI.

The time behavior is divided into three phases: early time ($t < 1$ ms), intermediate time (1 μs $\leq t \leq$ 1 sec), and late time or MHD-EMP ($t > 1$ sec). The early-time portion, $E_1(t)$, is attributed to the prompt gamma rays from the weapon. This part is usually called HEMP, although, strictly speaking, HEMP also means the entire signal. The intermediate-time portion, $E_2(t)$, is generated by secondary gamma-ray scattering and other scattering processes that occur after the first wave of prompt gamma-ray scattering. The late-time signal, $E_3(t)$, is identified as the MHD signal. This data sheet pertains to the $E_1(t)$ signal since it is the most pervasive and important.

DATA SHEET 20.5. HEMP CIRCUMVENTION TECHNIQUES

Developing Critical Technology Parameter	Techniques that provide a form of indirect equipment hardening against the impact of HEMP. In some cases, instead of hardening a system's components, the system can be isolated from those elements that would couple electromagnetic energy into it and cause damage or upset. Meaningful levels of reducing unwanted electromagnetic signals are useful.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes and algorithms that reduce unwanted electromagnetic fields.
Major Commercial Applications	Systems requiring electromagnetic isolation and/or reduction of unwanted electromagnetic fields in selected locations.
Affordability	Moderate. Highly systems dependent.

BACKGROUND

Circumvention techniques are a form of indirect equipment hardening against the impact of HEMP. In some cases, instead of hardening a system's components, the system can be isolated from those elements that would couple electromagnetic energy into it and cause damage or upset. For example, a communication station can be isolated from external power connections by a motor-generator combination with a nonmetallic drive shaft. Similarly, other external connections can be protected through fiber-optic technology.

The ability to apply circumvention techniques successfully requires a thorough understanding of electromagnetic coupling between the incident HEMP field and the system. Analysis of the effects on a system shows where the system is susceptible. Using a wide variety of tools from EMC, EMI, and computer software, we can minimize the adverse effects of HEMP. The combination of these tools is virtually limitless but is highly system dependent and may be limited by geometric constraints and practical limitations.

DATA SHEET 20.5. BUILT-IN TEST EQUIPMENT (BITE)

Developing Critical Technology Parameter	Equipment that accurately depicts the level of hardness against the HEMP threat during the lifetime of the system. The equipment must be highly reliable and cost effective. Equipment that produces meaningful levels of improvement over current capabilities is useful.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software that is integrated into BITE equipment.
Major Commercial Applications	Electrical utilities, transportation systems, information systems, energy systems, and so forth.
Affordability	Moderate. Increases with system size.

BACKGROUND

This technology pertains to specially designed BITE and onboard components or subassemblies containing combined software and hardware techniques that assess the performance of critical items' system-level HEMP hardness during a system's lifetime. Significant effort is required initially to understand and implement hardness techniques against the HEMP threat.

The normal operation of a system causes inevitable equipment degradation. However, BITE reduces greatly the cost of maintaining the desired hardness because it obviates the need of manual testing for hardness integrity. Efficient implementation of BITE is a critical element in maintaining the survivability of a system.

DATA SHEET 20.5. HEMP ENVIRONMENT COMPUTATION

Developing Critical Technology Parameter	Air chemistry models that are able to incorporate fast rising ($t_r < 2$ ns) radiation pulses for early-time HEMP; specialized neutron and gamma-ray radiation transport calculations that produce detailed currents and ionization rates for intermediate-time HEMP environments; time-dependent currents and ionization rates derived from neutron-inelastic and capture-transport calculations for use in intermediate-time HEMP environments; and MHD-EMP models that establish optimum procedures for calculating the late-time variations of the geomagnetic field caused by a high-altitude nuclear burst.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	State-of-the-art “software” (codes and algorithms) for computing HEMP environments that contain validated techniques or experimental data associated with the prediction of nuclear-generated HEMP.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

This item deals with predicting the HEMP environment from physical and chemical models; developing related computational models, algorithms, and computer codes; and validating code predictions against results from nuclear detonations or simulations of nuclear detonations. The theoretical models must predict nuclear-generated HEMP environments from the nuclear yield and incorporate ionization process and coupled charged particle and neutral particle transport in the presence of the geomagnetic field.

Air chemistry models that deal successfully with nanosecond and subnanosecond electromagnetic and radiation pulses are exceptionally difficult to devise and pertain exclusively to nuclear explosions. Nonohmic air conductivity and nonequilibrium air chemistry models are appropriate. Ohmic models and quasi-equilibrium air chemistry models appropriate for slower pulses are simple and have been available for several decades in the open literature.

Neutron and gamma radiation transport in the intermediate-time regime had been a difficult problem that was solved only in the latter part of the 1980s. These transport processes are important because they provide secondary sources of ionization and current, leading to the $E_2(t)$ (intermediate) part of the HEMP waveform. Transport codes solving this problem employ special methods to achieve needed deep-penetration results with acceptable statistics.

DATA SHEET 20.5. HEMP COUPLING

Developing Critical Technology Parameter	Theoretical models for predicting the coupling of the electromagnetic field into a system and the coupling of the interior field to mission-critical components and systems. Of particular interest are those models that can predict the net effects on mission-critical systems to < 10 dB.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Codes and algorithms for computing HEMP electromagnetic coupling that has been validated from HEMP simulations and contains any of the following features: models or related data for specially designed hardening features for reducing HEMP coupling and specially designed empirical coupling factors derived from HEMP simulations.
Major Commercial Applications	EMC and EMI.
Affordability	Expensive. Increases with system size.

BACKGROUND

To ensure that military systems can survive all aspects of the electromagnetic field produced by a high-altitude nuclear burst, the key issue is to reduce the electromagnetic fields that strike mission-critical equipment to levels that cause neither upset nor damage. This includes E_1, E_2, and E_3. The fundamental building block for hardening systems against HEMP is to understand and organize the sequence of EMP interactions within a system. This is accomplished using a topological approach to hardening. The result of this topological approach is the zonal method of hardening shown in Figures 20.5-5 and 20.5-6.

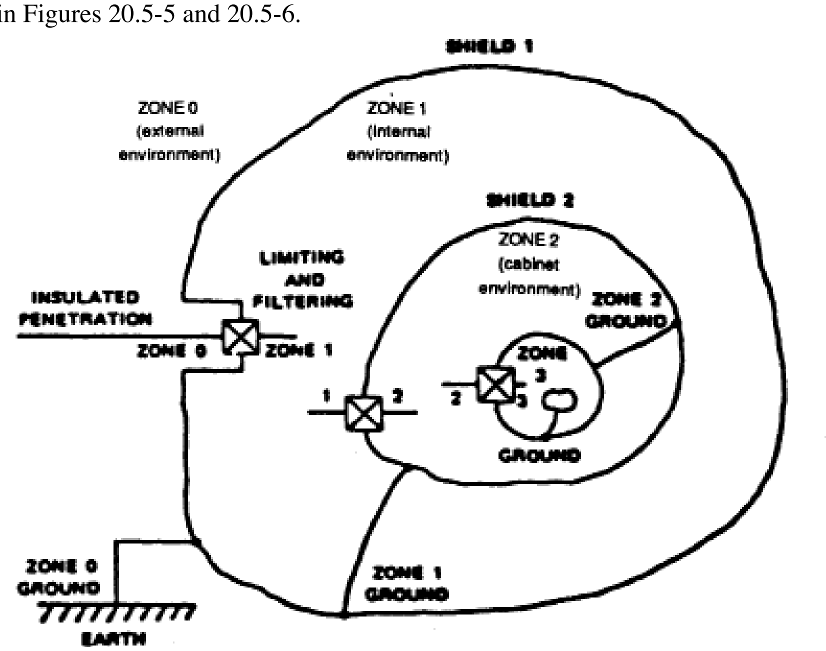
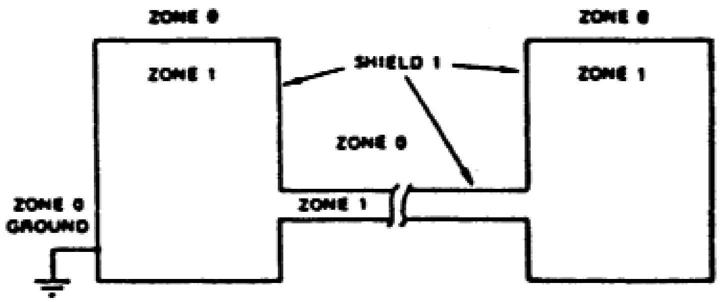
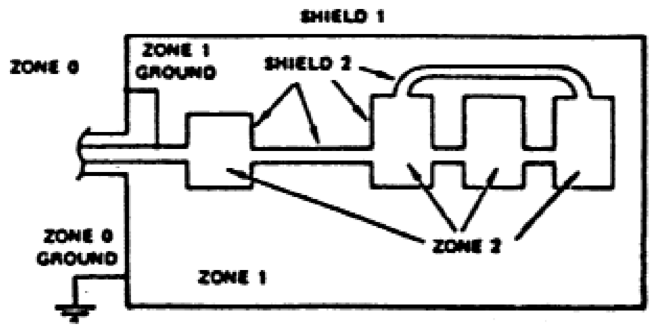


Figure 20.5-5. Shielding and Grounding Zones in a Complex Facility (Source: Reference 1)



(a) Shielded buildings connected by shielded cable



(b) Interconnected cabinets

Figure 20.5-6. Topology of Interconnected Regions (Source: Reference 1)

Each of the zones shown in Figure 20.5-5 contains cables and other electronic hardware. Determining the coupling between the cables and electronic hardware and the penetration of the electromagnetic radiation between the zones is a critical technical challenge. We can determine the susceptibility and survivability of mission-critical equipment only when this part of the problem is handled correctly.

CITED REFERENCE

1. E.F. Vance, "Electromagnetic-Interference Control," *IEEE Trans. Electromagn. Compat.,* Vol. EMC-22, 1980, pp. 319–328.

DATA SHEET 20.5. HARDNESS SURVEILLANCE SUBSYSTEMS

Developing Critical Technology Parameter	Surveillance and diagnostic techniques and hardware that identify incipient breakdown in HEMP hardness. Any meaningful level is of interest.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software that supports specially designed subsystems that contribute to military system-level hardness surveillance assessments.
Major Commercial Applications	Electrical utilities, transportation systems, information systems, energy systems, and so forth.
Affordability	Moderate.

BACKGROUND

This topic pertains to surveillance and diagnostics techniques and hardware that form an integral part of hardness maintenance procedures for mission-critical systems. These subsystems monitor functions and degradation in field-use of the most HEMP-sensitive elements within a system. This technology is essential for proper operation and life-cycle maintenance in the field.

DATA SHEET 20.5. HEMP PULSE GENERATOR

Developing Critical Technology Parameter	Pulse generators capable of delivering rates of voltage rise > 1 MV/ns into < 100 ohms or rates of current rise > 10 kA/ns into impedances > 100 ohms into a port on a system.
Critical Materials	Electrical insulating materials that can hold off transient electric fields in the megavolt-per-centimeter range
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

The HEMP pulser generates the signal into the apex of the radiating antenna of a HEMP simulator. Methods for integrating these technologies to produce HEMP waveforms that have risetimes above several nanoseconds and fall times in the few-microsecond range are universally known. This widely used technology is the Marx-peaking circuit with a self-closing, single-channel output switch. Both gas (usually high-pressure SF_6) and liquid (usually oil) switches are used as the switch that generates the output risetime.

The Marx is a universal technology and scalable to any voltage needed. Numerous scalable peaking capacitor designs that do not limit performance except possibly for high-frequency spectral purity are also readily available.

DATA SHEET 20.5. PEAKING CAPACITOR

Developing Critical Technology Parameter	Peaking capacitors with self-resonances > 1 GHz or using techniques to suppress self-resonances and operating at mean stress (mean electric field) > 5 kV/mil.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Most of the high-voltage and high-energy storage systems, such as the Marx generators, have too much inductance to produce risetimes under 10 ns. The most common method for correcting for this condition is to introduce a "peaking" circuit that allows the transfer of energy to a capacitor placed at the output stage that has low inductance. Figure 20.5-7 shows how the peaking circuit allows the Marx to be used in HEMP simulation.

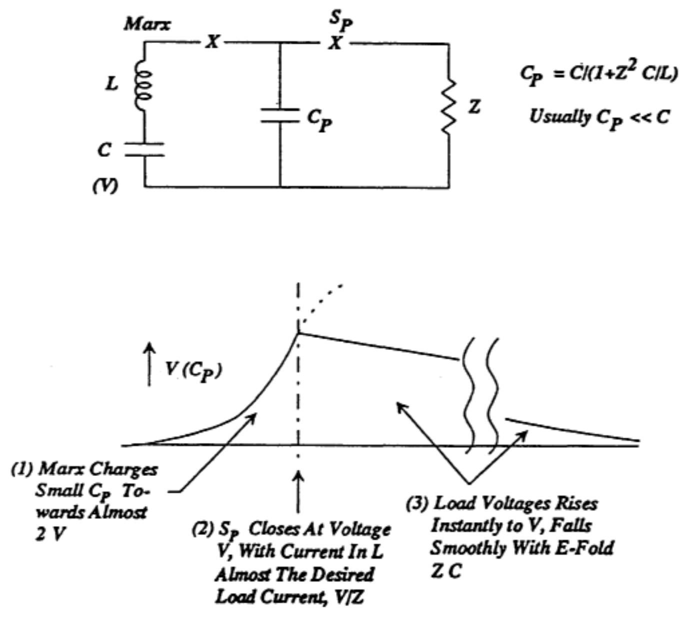


Figure 20.5-7. Peaking Circuit Used With Marx Generator (Source: Reference 1)

The physical size of the peaking capacitor can result in certain undesirable resonances that cause holes in the spectrum (missing frequencies). The comparative HEMP Fourier spectrum shows this effect. The design of a peaking capacitor is a critical technology in the development of a HEMP simulator.

CITED REFERENCE

1. C.E. Baum, "EMP Simulators for Various Types of Nuclear EMP Environments: An Interim Categorization," *IEEE Trans. Antennas Propagat.*, Vol. AP-26, January 1978, pp. 35–53.

DATA SHEET 20-5. SWITCHES

Developing Critical Technology Parameter	Switches that can be used in HEMP simulators to generate voltages > 1 MV with risetimes < 1 ns per megavolt of generated voltage or per 20 kA of generated current.
Critical Materials	A gas switch using SF_6 or an oil switch made on the basis of weight and breakdown strength, with the gas switch being lighter and the oil switch providing shorter risetimes at higher operating voltages.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Inexpensive.

BACKGROUND

Risetimes approaching 1 ns can be achieved by the basic ingredients of a Marx generator/peaking circuit/self-closing single-channel output switch for output voltages of 1 MV or less. Two basic types of switches used in conjunction with the Marx generator are a gas switch, such as SF_6, or an oil switch. The decision is often made on the basis of weight and breakdown strength, with the gas switch being lighter and the oil switch providing shorter risetimes at higher operating voltages, especially with fast changing switches.

Following is a summary of switch risetime for standard oil and gas switches:

- Gas switches give ~ 1 ns/MV, mainly because of inductance.
- Gas switches give shorter risetimes than oil switches at ≤ 5 MV or ≤ 50 kA.
- Oil switches may be faster at ≥ 5 MV, 50 kA.
- A gas switch is preferred when weight is an important factor.
- Gas switches result in lower pre-pulse (permittivity ≥ 1 vs. 2.3 for oil).

DATA SHEET 20.5. FADING DISPERSIVE COMMUNICATIONS CHANNELS

Developing Critical Technology Parameter	Simulate radio frequency (RF) propagation through disturbed ionosphere generated by high-altitude nuclear detonations; compute frequency-selective bandwidth, coherence time, SNR, and bit error rate (BER). The range of interest is for frequency selective bandwidths > 1 MHz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Validated computer codes and algorithms integrated with HITL that predict the space-time ionospheric plasma concentration, frequency-selective bandwidth, and coherence time in a nuclear-disturbed ionosphere.
Major Commercial Applications	None identified.
Affordability	Moderately expensive.

BACKGROUND

Nuclear detonations in the atmosphere can adversely affect the performance of communication and radar systems. The degree to which these systems are affected depends on factors such as HOB, weapon yield, time of day, cloud cover, latitude and longitude, electromagnetic wave propagation path, and time following the detonation. For communications systems and radar, the unwanted effects of nuclear detonations are attributed to the improved electron density and structure that the detonation creates in the atmosphere.

DATA SHEET 20.5. OPTICAL AND INFRARED (IR) SIMULATORS

Developing Critical Technology Parameter	Simulate propagation of IR (0.8–30 μm), visible (0.4–0.8 μm), and UV (0.01–0.4 μm) radiation in background environments generated by high-altitude nuclear detonations using HITL.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Validated computer codes and algorithms integrated with HITL that calculate high-altitude nuclear environments and predict propagation for IR/visible/UV signals.
Major Commercial Applications	None identified.
Affordability	Moderately expensive.

BACKGROUND

Nuclear detonations in the atmosphere can adversely affect the performance of military passive and active sensor systems. The degree to which these systems are affected is scenario dependent on factors such as HOB, weapon yield, time of day, cloud cover, latitude and longitude, electromagnetic wave propagation path, and time following the detonation. The most important problems for IR, visible, and UV sensor systems are the IR, visible, and UV radiation emanating from the heated regions. Laser communication systems also may be susceptible to the background IR radiation of a fireball or heated region when in the receiver's FOV.

The main sources of high-altitude long-wave infrared (LWIR) radiation are plasma emission, molecular and atomic emission from excited states, and, to a lesser extent, emission from uranium oxide. These emissions are functions of electron density.

To detect and track RVs against nuclear backgrounds, we must determine the power spectrum of optical emissions, and, subsequently, devise optical filtering techniques to suppress IR clutter. Since the power spectrum of optical emissions changes with time, the implementation of filtering techniques that adapt to changes in time is desirable. However, although these filtering techniques can improve the ability to suppress clutter, they may be difficult to implement and may require a suitable experience base. Because the nuclear test ban treaties prohibit the atmospheric testing of nuclear weapons, simulation is the only way to evaluate the performance of sensor systems.

DATA SHEET 20.5. PLASMA CONCENTRATION

Developing Critical Technology Parameter	Identify the electrochemical interactions in the ionosphere resulting from a high-altitude nuclear detonation as a function of HOB, weapon yield, time of day, cloud cover, and latitude and longitude.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes to predict the time- and space-dependent electron concentration and concentration of radiating species.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

Nuclear detonations in the atmosphere can adversely affect the performance of military communication and navigation systems, radar, and passive and active sensor systems. The degree to which these systems are affected depends on factors such as HOB, weapon yield, time of day, cloud cover, latitude and longitude, electromagnetic wave propagation path, and time following the detonation. For communications systems and radar, the unwanted effects of nuclear detonations are attributed to the improved electron density and structure that the detonation creates in the atmosphere. The most important problems for IR, visible, and UV sensor systems are the IR, visible, and UV radiation emanating from the heated regions. Laser communication systems also may be susceptible to the background IR radiation of a fireball or heated region when in the receiver's FOV.

The prediction of optical backgrounds is a computationally intensive task because a large number of atmospheric atomica and molecular species contribute to the optical emission. To compute these backgrounds, we must first determine the electrochemical reactions and develop sophisticated computer models.

SECTION 20.6—UNDERGROUND WEAPONS EFFECTS SIMULATION

Highlights

- Full-yield nuclear tests are the only way to produce concurrently all the relevant nuclear weapons effects simultaneously.
- Underground nuclear weapons effects tests (UGWETs) can provide insight into weapon performance, nuclear radiation effects (TREE and SGEMP), shock, thermal effects, and SREMP.
- Complete containment of radioactive debris is essential to prevent the release of harmful radioactivity into the atmosphere.
- To minimize greatly the release of radioactive material, a fast-acting mechanical closure is necessary.
- Underground nuclear testing is expensive.

OVERVIEW

This section identifies specific technologies needed for conducting safe and effective UGWETs. These technologies include generation of the nuclear environment for demonstrating the S&H of military equipment and materials and for studying basic nuclear effect phenomenology. Specific technologies include:

- Horizontal emplacement of the device
- Providing evacuated horizontal-line-of-sight (HLOS) tubes for viewing the detonation
- Mechanical closures to prevent debris from traveling through the HLOS tube to the experiment station that measures the radiation and shock environment and the response of systems
- Scattering station design
- The computer codes necessary to understand the results of the experiments.

BACKGROUND

For over 30 years, the United States has conducted UGWETs to assess the effects of nuclear explosions on U.S. military systems. Figure 20.6-1 is a sketch of an underground nuclear detonation that shows the generation of SREMP, cratering, and a silo model used for examining the effects of ground shock.

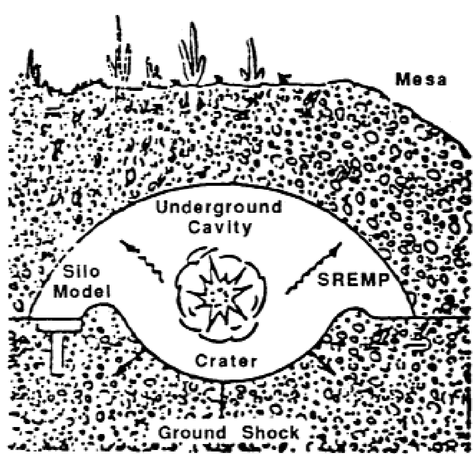


Figure 20.6-1. Sketch of Underground Nuclear Detonation (Source: Reference 1)

For effects testing, horizontal emplacement tests (HETs) are preferred over vertical emplacement tests because the emplacement of device and test equipment is simplified. HLOS tunnels provide greater experiment flexibility and access. Vertical shaft tests are less expensive but only provide a limited exposure area because of the risk associated with containment when the crater is formed. The need to excavate large cavities for placing the "test samples" and for constructing appropriate environments for those samples (e.g., a vacuum for reentry bodies) requires that HETs be conducted in terrain such as a mesa or mountainside. In principle, nuclear effects tests could also be conducted inside a deep mine.

The object of an HET is to allow nuclear radiation to reach the test object while preventing this object from being destroyed by the other effects. This enables scientists to recover the test instrumentation. Such a test requires redundant containment vessels. The first containment vessel surrounds the device. The second containment vessel surrounds all the experiment to protect the tunnel system if the inner vessel fails and the experimental equipment is lost. The third containment vessel ensures that no radiation escapes into the atmosphere—even if the experimental equipment is lost and the tunnel system is contaminated. Figure 20.6-2 is a schematic of the first containment vessel.

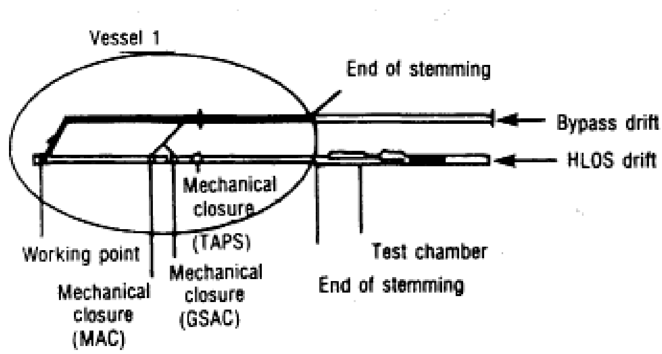


Figure 20.6-2. Schematic of an HLOS Pipe System Contained Within Vessel 1 (Source: Reference 2)

Not all experiments require "direct" nuclear radiation. Many are suitable for use with a scattered (lower intensity) beam produced in a scatter station—typically made with appropriate nuclear and atomic properties to deflect the correct wavelength and intensity of radiation. The design of these scatter stations requires technical skill and experience so that the scattered radiation is properly tailored for its intended use. An incorrectly designed station could mean that the test object is exposed to incorrect radiation types or intensities, which could significantly reduce the value of the test. Figure 20.6-3 is a schematic of a scattering station design.

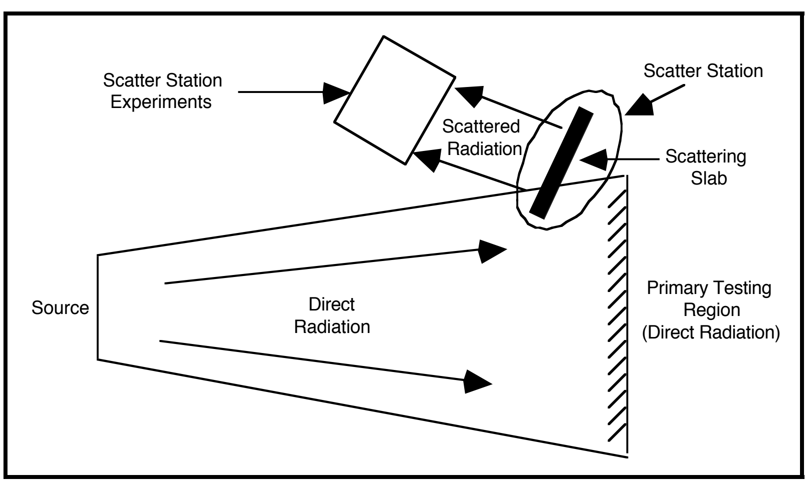


Figure 20.6-3. Schematic of Scattering Station

CITED REFERENCES

1. NTS Tour Information Brochure, DNA, Available from the DNA Field Office, Las Vegas, NV.

2. U.S. Congress, Office of Technology Assessment, *The Containment of Underground Nuclear Explosions*, OTA-ISC-414, Washington, DC: U.S. Government Printing Office, October 1989.

LIST OF TECHNOLOGY DATA SHEETS
20.6. UNDERGROUND WEAPONS EFFECTS SIMULATION

DATA SHEET 20.6. UNDERGROUND WEAPONS EFFECTS TESTBED

Developing Critical Technology Parameter	A major critical technology is radioactive release containment that complies with environmental constraints and detection. This can be accomplished using several novel devices and techniques in an integrated containment design. Mechanical and cable-gas-flow blocking designs that withstand up to 1,000 psi for up to 1 hr are used. Mechanical devices that isolate portions of the HLOS pipe within 100 ms after exposure to radiation are also effective containment techniques. Techniques for recording analog signals with frequency content > 250 MHz; timing and firing systems that provide a probability of failure < 0.01 percent are essential. In addition, measurement systems have to permit measurement and recording of X-ray fluence > 0.1 cal/cm^2 in < 50 ns and time-resolved spectra in the photon energy range of 10 eV to 500 keV. Measuring and recording neutron spectrum at flux levels > 10^{19} n/cm^2-sec of 14 MeV neutrons and measuring the complete time-dependent flux of gamma rays are also essential.
Critical Materials	Stemming materials.
Unique Test, Production, Inspection Equipment	Specially designed mechanical closures that prevent the uncontrolled release of gas or debris; diffusion or cryogenic pumps that maintain < 1 Torr over a total pipe system > 500 ft in length; manufacturing equipment that can maintain two-dimensional (2-D) uniformity of < 1 percent; detectors that measure X-ray fluence > 0.1 cal/cm^2; stress and particle motion gauges capable of measuring stress > 1 kbar and velocities > 10 m/s; airblast gauges with < 2 ms risetime.
Unique Software	Computer codes and algorithms for computing the following: coupled radiation hydrodynamics flow [especially in 2-D or three-dimensional (3-D) geometry]; high-temperature opacity, X-ray deposition, and material response; shock propagation in the ground; airblast; EOS; stress waves in and around nuclear explosive cavities; Maxwell's equations in ionized air; and X-ray blow-off. Of special interest are those codes and algorithms that have been validated against nuclear test data.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

The United States has conducted UGWETs to assess the effects of nuclear explosions on U.S. military systems. Until recently, the United States had conducted about a dozen UGTs each year. Each test was designed to contain the underground radioactive release. With a few exceptions, U.S. containment has been extremely successful. In addition to the military objectives of determining system survivability, the technologies associated with the containment of radioactive material are important elements of the U.S. underground nuclear testing program.

DATA SHEET 20.6. SCATTERING STATION DESIGN

Developing Critical Technology Parameter	Parameters and rules for designing scatter stations that facilitate the acquisition of information on system response to the nuclear and electromagnetic radiation generated in UGWETs.
Critical Materials	Lithium hydride.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Substantiated computer codes and algorithms that facilitate the design of scatter stations and collectively incorporate the effects of electromagnetic and X-ray environments.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

All the experiments do not require direct nuclear radiation. The nuclear radiation for these experiments is obtained by using a scatter station (see Figure 20.6-4). The direct beam interacts with a plastic scattering slab. This interaction produces indirect (scattered) nuclear radiation in the region of the experiment.

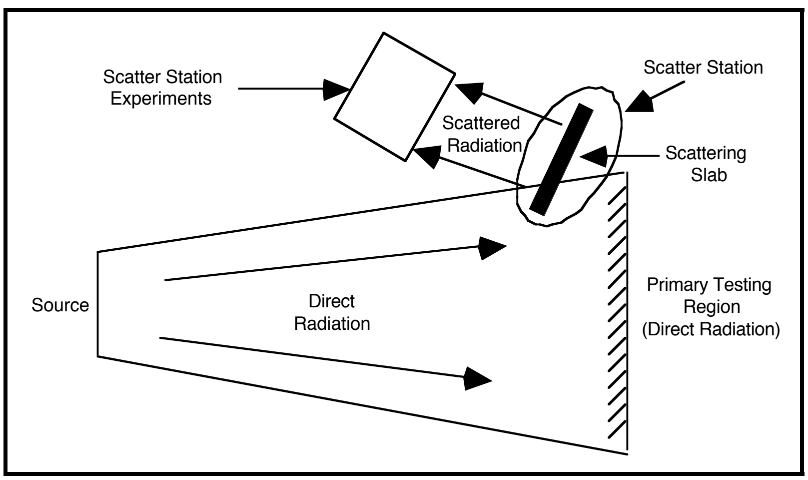


Figure 20.6-4. Schematic of Scattering Station

Figure 20.6-5 shows a collection of electronic systems exposed to indirect nuclear radiation. Since scattering produces a change in the energy spectrum of the nuclear radiation, developing a scatter station requires considerable technical skill. The technologies for designing the scatter station and tailoring the scattered radiation to meet electronic system survivability test are technical challenges.

Figure 20.6-5. Experiments Used in Scatter Station (Source: Reference 1)

CITED REFERENCE

1. NTS Tour Information Brochure, DNA, available from DNA Field Office, Las Vegas, NV.

DATA SHEET 20.6. RADIATION HYDRODYNAMICS FLOW

Developing Critical Technology Parameter	Developing robust theoretical models and computer algorithms for predicting radiation hydrodynamic flow is a major technical challenge. In this region, there is strong coupling between the sources of electromagnetic radiation at high temperature and fluid flow. Because adequately defining all the interactions between the radiation environment and fluid is often difficult, deducing transport coefficients and other parameters from UGT environments is necessary.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Substantiated computer codes and algorithms that compute radiation hydrodynamics flow for the range of parameters relevant to an underground nuclear test environment.
Major Commercial Applications	None identified.
Affordability	Moderately expensive since it is connected with underground testing.

BACKGROUND

In an underground nuclear explosion, a blast wave is initially formed in the air surrounding the detonation. This takes place in the detonation cavity. This blast wave initially includes debris from the weapon and the air, which is at atmospheric pressure. For most blast-wave problems involving chemical explosions, the concept of local thermal equilibrium (LTE) is applicable. LTE means that an EOS determines the relative concentration of all the constituents in every infinitesimal region of space. Equilibrium statistical mechanics are used to determine the EOS. All constituents are at the same local temperature.

For nuclear detonations that take place in the detonation chamber, the temperature of the air is so high that the transport equations have to be modified in two ways:

- First, the energy density of the electromagnetic radiation has to be included in the transport process. Predicting radiation transport requires a separate transport equation (e.g., the Boltzmann equation).
- The second change occurs when the assumption of LTE ceases to be valid. Separate transport equations for each chemical constituent in the gas are then required. The concept of a single local temperature becomes questionable. Approximations are necessary to make the combination of fluid and radiation transport equations tractable.

Although the radiation and transport equation can be formulated theoretically, knowing its constituents is necessary to make accurate predictions. This problem becomes even more difficult when the initial blast wave hits the wall of the chamber, crushing the solid structure. When this happens, many more elements are added to the transport processes, making the development of an accurate combined radiation and fluid model very difficult. Improvements in characterizing the model are made by deducing transport parameters from the UGTs. The key to accomplishing this task with high fidelity is to develop a theoretical model that is amenable to accommodating empirical information.

DATA SHEET 20.6. HIGH-TEMPERATURE OPACITY

Developing Critical Technology Parameter	The transparency of a material is the ratio of the transmitted to the incident electromagnetic radiation. The opacity is the reciprocal of the transparency. *Mean opacities* can be computed when the radiation field is in LTE. To calculate the temperature for LTE, a system's energy states for photon transitions have to be described adequately. The difficulty of this calculation increases as the atomic number of an element increases. To improve the capability of predicting radiation transport for underground nuclear weapons effects testing, we must be able to calculate the opacities of materials of atomic number > 71 and for photon energies from 50 to 20,000 eV.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Substantiated computer codes and algorithms that compute high-temperature opacity (including ionized gas contributions); multigroup opacity libraries created by such codes.
Major Commercial Applications	None identified.
Affordability	None identified.

BACKGROUND

In an underground nuclear explosion, a blast wave is initially formed in the air surrounding the detonation. This takes place in the detonation cavity. This blast wave initially includes debris from the weapon and the air, which is at atmospheric pressure. For most blast-wave problems involving chemical explosions, the concept of LTE is applicable. LTE means that an EOS determines the relative concentration of all the constituents in every infinitesimal region of space. Equilibrium statistical mechanics are used to determine the EOS. All constituents are at the same local temperature.

For nuclear detonations that take place in the detonation chamber, the temperature of the air is so high that the transport equations have to be modified in two ways:

- First, the energy density of the electromagnetic radiation has to be included in the transport process. Predicting radiation transport requires a separate transport equation (e.g., the Boltzmann equation).
- The second change occurs when the assumption of LTE ceases to be valid. Separate transport equations for each chemical constituent in the gas are then required. The concept of a single local temperature becomes questionable. Approximations are necessary to make the combination of fluid and radiation transport equations tractable.

DATA SHEET 20.6. MATERIAL RESPONSE

Developing Critical Technology Parameter	The developing critical technical parameters are material thermal conduction and electron transport parameters deduced empirically from UGWETs. This technology pertains to predicting the response of thin-film optical systems to high-energy deposition rates caused by nuclear-weapon-generated X-rays. Typically, the energy deposition occurs between 1 to 100 ns. Depending on the energy of the X-rays, this radiation is absorbed at varying depths in materials. The higher the energy of the X-rays, the greater the depth. For nuclear-weapon-generated X-rays, the depths may range from a few hundredths of a millimeter to the millimeter range. The temperature and pressure of the radiated material are raised into a regime that has been relatively unexplored. For example, the temperatures may reach tens of thousands of degrees Kelvin. To determine the response of the material to this pulse of energy, determining the EOS is necessary and, from the EOS, the thermal conduction and electron transport parameters. The theory that provides these transport coefficients is incomplete for some materials used on space platforms. For this reason and also because of the inherent uncertainties connected with the experimental configuration, enhancing the fidelity of theoretical models of thermal conduction and electron transport parameters with empirically deduced parameters from UGTs is often necessary. This improves the ability to predict the response of thin-film optical systems to nuclear-weapon-generated X-rays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Substantiated computer codes and algorithms that can predict X-ray deposition and material response of thin-film optical systems.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

A nuclear weapon emits copious amounts of X-rays that cover a wide spectrum of energies. In referring to X-ray-produced nuclear effects, the common practice is to refer to “hot X-rays” and “cold X-rays.” The demarcation is not precise, but it relates to the fact that the more energetic hot X-rays can penetrate the skin of an object and deposit energy in the interior, while the lower-energy cold X-rays deposit energy in the outer layer of an object. In both cases, when a large amount of energy is deposited in a small distance in a short time interval, a shock wave is produced in the materials.

X-rays from a nuclear burst typically deposit their energy near the target surface between 1 to 100 ns. For cold X-rays, the energy is absorbed in a few hundredths of a millimeter of the outer surface. Within this short time scale of energy deposition, the material exhibits little motion and virtually all the incident X-ray energy increases the internal energy of the material. When the total energy deposition is high enough, the material is raised to the vapor state at high pressure, leading to the creation of a shock wave into the nonvaporized material.

The type of shock wave just described is attributed to the cold X-rays (those absorbed near the surface), and the resulting shock wave is attributed to impulse loading. The mathematical description of shock waves in solid materials is known. A critical aspect in determining system survivability is knowledge of the physical properties of the material undergoing shock. Enhancing the fidelity of theoretical models of thermal conduction and electron transport parameters with empirically deduced parameters from UGTs is often necessary. This improves the ability to predict the response of thin-film optical systems to nuclear-weapon-generated X-rays.

DATA SHEET 20.6. EQUATION OF STATE (EOS)

Developing Critical Technology Parameter	The critical technical parameters are those experimentally validated parameters that define the EOS under high temperatures (tens of thousands of degrees Kelvin) and pressures typical of those produced in materials by incident nuclear radiation. In large part, the EOS provides the information required for predicting shock propagation and the time-dependent transport of material and energy during irradiation from a nuclear detonation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Substantiated computer codes and algorithms that can compute shock propagation and that contain EOS information at high pressures and temperatures.
Major Commercial Applications	None identified.
Affordability	Expensive to very expensive (if experiments are required to support theory).

BACKGROUND

The EOS is required to determine material energy transport coefficients under the high temperatures and pressures generated by the radiation flux from a nuclear weapon. Temperatures could reach tens of thousands of degrees Kelvin. Equilibrium statistical mechanics provides the theoretical basis for deriving the EOS under the conditions of LTE. This condition is a special case because it applies to a situation where, in a very small volume of material, the system is close to an equilibrium state. Intuitively, we would expect this condition to apply to processes whose temporal change is not rapid in comparison to the time scale associated with the forces that establish equilibrium between particles in the system.

When LTE applies, one can use a variety of theories to calculate the EOS. For example, the Maxwell-Boltzmann distribution is used to determine the EOS for a gas, Fermi-Dirac statistics are used to derive the electron distribution function in a solid, and Bose-Einstein statistics are used to derive the Planck radiation law. At high temperatures, ionized states exist, and the concentration of the levels are determined by the Saha equation, also derived on the basis of LTE.

Even though some general mathematical techniques can be used to determine the EOS for gases, liquids, and solids, the problem is extremely difficult at high temperatures. At these high temperatures, the number of system states in which a significant population might exist increases dramatically. Detailed information about the energy levels of these states is required to obtain a reliable determination of the EOS. Further complications arise when the material is composed of different elements.

In summary, the theoretical deduction of the EOS is recognized as a formidable problem. For this reason, the development of theories and methods that can accommodate experimental data into the models is a vital technology in predicting transport properties of materials under high temperatures and pressures.

DATA SHEET 20.6. STRESS WAVES

Developing Critical Technology Parameter	The critical technology parameters are those used to predict the behavior of stress waves in underground testing environments. Several components of stress waves are unique to underground testing environments. Predicting stress wave parameters in soil, rock, and other structures prevalent in an underground testing environment is difficult because of the random and irregular nature of the material. Deducing empirical data for shock-wave parameters from nuclear weapons effect tests conducted in explosive cavities and incorporating these data into a theoretical model are essential for designing underground nuclear weapons tests.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes and algorithms that analyze stress waves from nuclear explosive cavities that use one-dimensional (1-D) and 2-D validated Lagrangian ground-motion techniques containing state-of-the-art constituent models.
Major Commercial Applications	Evaluating earthquakes.
Affordability	Moderate.

BACKGROUND

The nuclear explosion generated in an underground cavity generates an intense shock wave that originates at the location of the detonation. This shock wave hits the interior walls, crushing them and also generating stress waves through the surrounding structure. Predicting the behavior of the stress waves as they travel through the underground is a complex task because of the irregular composition of the earth's material. Nevertheless, knowing this information is necessary to ensure that the equipment does not get damaged.

Theoretical predictions can provide a good mathematical framework for making theoretical predictions. Stress wave parameters deduced from tests themselves can provide more realistic predictions of stress wave behavior.

DATA SHEET 20.6. X-RAY BLOW OFF

Developing Critical Technology Parameter	The critical technology parameters are theoretical X-ray blow-off material models that have been calibrated against nuclear detonations and/or incorporate parameters deduced from nuclear weapons effects testing. The need for calibrated theoretical models stems from the complexity of the energy deposition process. This involves knowledge of the energy spectrum of the incoming X-ray radiation and the energy transport parameters determined, in part, from the EOS.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes and algorithms for computing X-ray induced blow-off impulse and the associated data base parameters. Of particular interest are those models that have been calibrated against weapons effects test data.
Major Commercial Applications	None identified.
Affordability	Moderate to very expensive (if experimental data are required).

BACKGROUND

A nuclear weapon emits copious amounts of X-rays that cover a wide spectrum of energies. In referring to X-ray-produced nuclear effects, the common practice is to refer to "hot X-rays" and "cold X-rays." The demarcation is not precise, but it relates to the fact that the more energetic hot X-rays can penetrate the skin of an object and deposit energy in the interior, while the lower-energy cold X-rays deposit energy in the outer layer of an object. In both cases, when a large amount of energy is deposited in a small distance in a short time interval, a shock wave is produced in the materials.

X-rays from a nuclear burst typically deposit their energy near the target surface between 1 to 100 ns. For cold X-rays, the energy is absorbed in a few hundredths of a millimeter of the outer surface. Within this short time scale of energy deposition, the material exhibits little motion and virtually all the incident X-ray energy increases the internal energy of the material. When the total energy deposition is high enough, the material is raised to the vapor state at high pressure, leading to the creation of a shock wave into the nonvaporized material. The type of shock wave just described is attributed to the cold X-rays (those absorbed near the surface), and the resulting shock wave is attributed to impulse loading.

For hot X-rays, which are capable of penetrating deeper into the structure, damage modes attributed to "whiplash" and "curling" must be considered. Whiplash is a body-bending mode caused by the heating of one side of an object. Curling is a late-time heating effect that causes the material property to enter the plastic range.

DATA SHEET 20.6. MEASUREMENT SYSTEMS

Developing Critical Technology Parameter	Critical technology parameters are the measurement of X-ray fluence exceeding 0.1 cal/cm^2 in the energy range between 10 eV and 500 keV and the complete time-dependent energy spectrum of gamma rays, SREMP parameters, thermal radiation, and shock and hydro parameters. Included is the time-integrated neutron energy spectrum in the range < 20 MeV. These measurement systems must perform in the hostile nuclear radiation environment created by a nuclear detonation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Research laboratories.
Affordability	Modest.

BACKGROUND

Measurement systems must operate in the environment created by an underground nuclear detonation. These measurement systems must be capable of measuring the time-dependent and time-integrated X-ray, neutron, and prompt gamma-ray spectrum for the entire duration of the nuclear detonation, earth stress, particle motion and shock characteristics, electric and magnetic fields, and thermal radiation.

Although different types of instruments are required to measure different physical quantities, all these instruments must function in the same nuclear-produced environment. Measurement systems are required to integrate high-frequency analog, high-speed digital electronic equipment, and fiber-optic link transfer systems for the collection, transmission, and storage of test data.

DATA SHEET 20.6. MECHANICAL ENCLOSURES

Developing Critical Technology Parameter	Specially designed mechanical closures capable of preventing the uncontrolled release of gases or debris from any portion of the HLOS pipe.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Very expensive.

BACKGROUND

This technology is of interest only for ensuring the containment of a nuclear explosion effects test. It specifically refers to the development and manufacture of the fast-acting closure (FAC), which is a large mechanical device that closes in a millisecond and creates a plug that seals the HLOS pipe. This plug prevents debris from flowing down the HLOS pipe. This debris could cause damage to the experiments and create a cavity gas leak path. The fabrication technique must be controlled carefully to ensure the proper ductility and strength needed to withstand the loads of pipe flow and stemming extrusion. The aspects of the flange design that transmit the stemming extrusion load to the concrete plugs are extremely unique.

After a horizontal tunnel test (HTT), scientists intend to recover the experimental instrumentation. The objective of these tests is to allow the nuclear radiation (X-rays, gamma rays, and neutrons) to reach the test object but to prevent the test object from being destroyed by the other effects. Because of the stringent containment requirements in HTTs, considerable redundancy exists in the HTT system. Designers achieved this redundancy by using three nested containment vessels. Each vessel is designed to contain independently a nuclear explosion. Figure 20.6-6 shows this configuration.

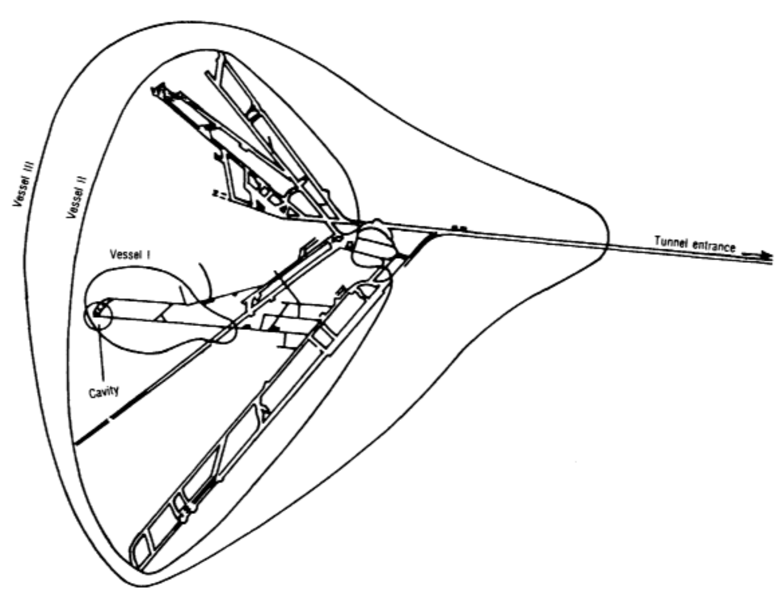


Figure 20.6-6. Plan View of Three Redundant Containment Vessels (Source: Reference 1)

Vessel I is designed to protect the experiment by preventing damage to the equipment and allowing it to be recovered. Vessel II is designed to protect the tunnel system so that it can be reused if Vessel I fails and the experimental equipment is lost. Vessel III is designed purely for containment so that radioactive material does not escape into the atmosphere even if the experimental equipment is lost and the tunnel system is contaminated.

CITED REFERENCE

1. U.S. Congress, Office of Technology Assessment, *The Containment of Underground Nuclear Explosions*, OTA-ISC-414, Washington, DC: U.S. Government Printing Office, October 1989.

DATA SHEET 20.6. DIFFUSION AND CRYOGENIC PUMPS

Developing Critical Technology Parameter	Specially designed diffusion or cryogenic vacuum pumps capable of maintaining much $< 10^{-3}$ Torr over a total pipe system that may be 1,300 feet in length (or longer) and may vary in diameter from 1 in. to 30 ft. Special diffusion or cryogenic vacuum system designs applicable to the unique environment of underground nuclear weapons effects testing.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

Attaining very high vacuum (generally defined to be less than 10^{-3} Torr) is a key element in the experimentation related to vulnerability tests where low-energy X-rays (i.e., those unable to penetrate a significant depth of the atmosphere) are important. Such low-energy photons are important in determining surface effects on various key elements of our space defense systems. The diffusion or cryogenic vacuum pumps also must be specially designed for UGT environments.

DATA SHEET 20.6. CRYSTAL FABRICATION EQUIPMENT

Developing Critical Technology Parameter	Specially designed fabrication equipment required for the manufacture of curved/ multilayer crystals capable of maintaining 2-D uniformity to < 1 percent and operating in the unique environment of UGWETs.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Research laboratories.
Affordability	Moderate.

BACKGROUND

One of the most important aspects of any weapons effects test is determining the spectral content of the radiation beam. Crystal fabrication equipment provides the capability of resolving incident radiation into its spectral components, thereby allowing for experimental tailoring based on device spectrum. This type of equipment would allow potential adversaries to analyze their own devices for spectral content and would allow them to test U.S. systems at that portion of spectral radiation most damaging to specific parts of these systems or subsystems. The crystal fabrication equipment also must be specially designed for UGT environments.

DATA SHEET 20.6. DETECTOR MANUFACTURING

Developing Critical Technology Parameter	Specially designed fabrication equipment and materials used for manufacturing detectors capable of measuring X-ray fluences at levels > 0.1 cal/cm^2. Specially designed fabrication equipment and materials used for manufacturing detectors capable of measuring X-ray fluences at levels > 0.1 cal/cm^2 in < 50 ns and operating in the unique UGWET environment.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	X-ray detectors for scientific investigations.
Affordability	Moderately expensive.

BACKGROUND

These detectors allow for an exact determination of the fluence incident upon experiments, thereby providing for an analysis of system performance on a sure-safe vs. sure-fail basis. This capability would allow hardening studies and tradeoffs based solely on tolerable damage incurred vs. radiation fluence received. These detectors also could promote significant advances in system hardening by allowing for exact exposure determinations. The detector manufacturing also must be specially designed for UGT environments.

DATA SHEET 20.6. X-RAY DIODES

Developing Critical Technology Parameter	Specially designed X-ray diodes capable of measuring X-ray fluences at levels > 0.1 cal/cm^2 in > 50 ns and operating in the unique UGWET environment. This includes coaxial X-ray diodes (CXRDs) and impedance matched X-ray diodes (MAXRDs).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

X-ray diodes can determine fluence of incident radiation, which then enables hardening and tradeoff studies to be developed. In addition, depending upon the manner in which the diode is used, spectral information of the incident radiation can also be obtained.

DATA SHEET 20.6. DIFFRACTION GRATINGS

Developing Critical Technology Parameter	Specially designed curved/multi-layer crystal diffraction gratings capable of resolving low-energy X-rays for measurement by some form of X-ray diode.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	X-ray measurement systems for scientific studies.
Affordability	Expensive.

BACKGROUND

Diffraction gratings produced from crystal fabrication equipment provide spectral determinations of the incident radiation, thereby allowing the type of damage desired to determine system stress. This knowledge allows for system defeat at the component or subsystem level.

DATA SHEET 20.6. COMPTON DIODES (CDs)

Developing Critical Technology Parameter	Specially designed CDs used in the measurement of gamma-ray radiation time history, to include impedance-matched CDs.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Expensive.

BACKGROUND

The release of gamma radiation (a product of the nuclear process) accompanies the detonation of a nuclear weapon. For a high-altitude nuclear detonation, the time history and total gamma-ray yield determine, in part, the HEMP wave shape produced. CDs can measure accurately the total gamma-ray yield and its temporal distribution. Since HEMP is a major factor in assessing the survivability of certain military systems, CDs can improve the design of devices to improve our ability to determine HEMP.

DATA SHEET 20.6. PARTICLE MOTION GAUGES

Developing Critical Technology Parameter	Critical technology parameters are the specially designed stress and particle motion gauges that are capable of measuring stress > 10 kbars and velocities > 100 m/sec in the intense radiation environment of a nuclear test.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Moderate.

BACKGROUND

The major technology is the ability of the particle motion gauge to operate in the radiation environment created by the nuclear detonation. Specifically, the issue is the development of methods for making measurements past the peak velocity and peak pressure stress under these conditions. The capability of measuring past the peak provides greater insight into the transient effects produced by nuclear detonations. The combination of radiation, thermal, and blast effects is unique to nuclear weapons and is useful only to those testing such devices or weapons.